Other books by G. Rattray Taylor

ECONOMICS FOR THE EXASPERATED
CONDITIONS OF HAPPINESS
ARE WORKERS HUMAN?
SEX IN HISTORY
THE ANGEL-MAKERS

Abridgement

THE MOTHERS
(*Robert Briffault*)

EYE ON RESEARCH

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DIAGRAMS IN TEXT

Who this book is for

One of the main purposes of the series of television programmes launched by the BBC Television Service in the autumn of 1957 under the title of *Eye on Research* was to provide the ordinary viewer with a general idea of what is going on in the broad field of scientific research—for, in this day and age, no one can call himself well-informed who has not at least a general idea of what scientists are trying to do.

These programmes aroused wide interest. But many viewers felt that they would like a chance to study the facts presented in the programmes at their leisure. Others wanted to read about programmes in the series which they had been unable to see. Hence this book, which presents eleven of these programmes in written form.

It is not a science-primer, but a series of up-to-date reports on scientific research, most of it hitherto only described in technical papers in scientific journals, if at all. So up to date is the *Eye on Research* series that leading scientists say they find it a useful way of keeping up with progress in fields other than their own. So, although this book has been written primarily for the non-expert, I believe it will also interest people with some knowledge of science, such as science students, technicians and engineers.

G. R. T.

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1

The Eye Opens

I WAS walking along Merrion Street, Dublin, one fine morning in August 1957, when I saw Mary Adams coming towards me, accompanied by a short, solid man with dark hair. Mary Adams, until her retirement in 1958, was assistant to Cecil McGivern, the man in charge of all the BBC's television programmes and later to Kenneth Adam, when McGivern became Deputy Director: her field was the informative and artistic side of television, as distinct from variety, plays and 'entertainment' generally. Mary Adams I knew, but the man, who turned out to be Aubrey Singer, was unknown to me. He was, in fact, an outside broadcast producer, and had acquired a considerable reputation by devising and producing the hour-long programme on the international geophysical year, *The Restless Sphere*, in which Prince Philip appeared as commentator.

It was in this way that I met the man with whom I was to travel so many thousands of miles in search of programmes for the *Eye on Research* series. I was in Dublin attending the annual meeting of the British Association. Mary Adams and Aubrey Singer had also come to it, seeking ideas for television programmes. They had decided to employ the BBC's outside broadcast teams to visit scientific laboratories and to report on what was going on in the world of scientific research. These 'OB units' as they are called, consist of mobile control-rooms, equipped to control three cameras. These cameras can be taken almost anywhere in vans, together with the necessary cables, lighting equipment, microphones, amplifiers, and so on.

Mary Adams and Aubrey Singer were also looking for someone who would act as a link between the scientist and the producer: someone who would know enough about science to understand what they were doing, enough about clear writing to simplify the scientists' explanations, and enough about television to know what

the producer was talking about when it came to the technicalities involved in constructing a programme.

Some two years earlier I had urged upon her a much more enterprising approach to the coverage of scientific research by television.

The treatment of science on BBC television has favoured the 'brains trust' type of programme, in which scientists answered viewers' questions. Often these questions were trivial—as when the Astronomer Royal was asked, in one programme, what causes the rainbow—a piece of information available in any elementary physics textbook, and known to most schoolboys. But even when they were complicated, they did not bring out the problems which the scientist faces, and tended to make the scientist look like a man who has all the answers, when really he is a man who is trying to find out some answers, and very well aware of how much he does not know.

Scientists are much more interested in the unknown than the known. And for the onlooker too, I felt, this is where the romance and excitement of science lies. How *can* one discover the answer to some puzzling problem: what *is* the cause of hay fever? Just what is it that the thousands of men who work within the high wire fences of the Atomic Energy Establishment at Harwell do for their living? How *do* parents pass to their children so many of their physical characteristics and features?

We are in a golden age of scientific discovery, when the frontiers of knowledge are being pushed back as never before. Scientists themselves feel the excitement of their work, though they may not always admit this.

So I welcomed the opportunity which the BBC thus gave me to try to convey some sense of this excitement to the viewer.

In this book I have described ten out of the first fifteen *Eye on Research* programmes (not counting two special programmes from the Brussels World Fair) together with the hour-long programme *Breakthrough*. The programmes I have left out are those where the appeal was so strongly visual that I did not feel that they would justify full-length written treatment.

In these eighteen programmes we achieved, I think, a good many of the aims with which I, at least, set out. We provided a broad picture of British research, both pure and applied; from universities and from government establishments, from private institutions and industrially-supported laboratories. We showed both large and

costly installations like the Bedford wind-tunnels and DIDO, and delicate small-scale work, as in the four biological programmes.

One professional critic, who cannot have been a very regular viewer, said that we had developed a regular pattern of visiting large government establishments. This was easy, he said, as all one had to do was to put the camera up and televise whatever came. His conclusion was as wrong as his premiss. One thing we learned was that the large establishment is especially difficult to convey. Visiting it, one may be impressed by the size, by the noise and the vibration, which convey a sense of terrific power. Seen on a small screen by a cosy fireside, all feeling of size tends to be lost, and the noise and vibration are muted, so that the sense of vast forces fails to come over.

On the contrary, it is the delicate manipulation and the subtle technique which fascinate viewers.

We started with the idea that, although we should make things as simple as we could, by using clear language and explanatory diagrams and demonstrations, we should not over-simplify. Much of science is now so complex that it cannot be made completely simple except by abandoning any real attempt to explain what is being done. This was particularly the case with the DNA programme. Several people told us that we aimed too high: the British public, they said, would not understand and would switch off.

The viewing figures we got—the audience fluctuated between six and nine million—justified our belief: so did the 'reaction index' which measures how much those who do view a programme enjoy it. In fact, the figures were so high, the BBC ordered them specially checked, thinking perhaps an error had been made. Besides all this, the many encouraging comments we received from other scientists showed that it is possible to build programmes which will contain something both for the scientifically trained and the untrained viewer.

The production of these programmes involved a degree of ingenuity on the part of the technical people concerned which, I imagine, must be far greater than has been called for in any other television series, and I should like to convey some impression of what they achieved. A good example was the programme *Up in the Clouds*, transmitted from Dr Mason's laboratory in Imperial College. Like most labs, the room is full of benches and experimental equipment, and, even after crowding these against the walls there is barely room to manœuvre a couple of bulky television cameras.

A more serious difficulty, however, consisted in the fact that almost all the demonstrations were small in scale and, in many cases, involved the use of microscopes. Ordinary television cameras, of course, cannot look directly through microscopes and special arrangements have to be made. What we usually do is to fit the microscope with a 'side tube'. This introduces a prism which turns some of the light through at right angles so that it leaves the microscope barrel sideways. We then fix up a small TV camera made for industrial purposes which can look directly into this side tube.

But there were additional difficulties. For instance, most of the work took place in specially-cooled chambers, intended to provide atmosphere similar to the cool interior of a cloud: as soon as the special lighting was shone on these chambers, they started to mist up. We were afraid we might even cause the ice-crystals to melt before the viewers could see them! Where microscopes were used, we had to 'overrun' the bulbs which provided illumination because these were only intended to give enough light for the human eye which is more sensitive than the best available camera. This meant, of course, that the bulbs were liable to burn out in the middle of the programme.

A difficulty which beset many programmes was that scientists distribute their work about the building; since television cameras, with their heavy wheeled mounts cannot be taken up and downstairs in the course of a programme, this often makes it difficult to present the various aspects of a piece of work in a single programme. In the case of *Up in the Clouds*, for example, the large tank which Mason used to reproduce the effect of a cloud unfolding, and which we wanted to show at the start of the programme as a symbol of the way in which the vast drama of weather can be reproduced in the laboratory in miniature, is situated in the basement of the building, so that it will be subject to as little vibration from traffic as possible.

But Mason's main lab is at the top of the building five floors above! Furthermore, I felt that we really needed *two* tanks, because the demonstration took place so rapidly that people might not get the point the first time it was shown. It was not possible simply to empty and refill the first tank in the time available—and, in any case, the water has to be allowed to become perfectly still for several hours before the experiment can be performed. We therefore had to bring in our own tanks. Locating two tanks with glass fronts about six feet high is harder than it sounds. They were finally supplied by

the Property Department of the BBC—but what they sent at first were tanks which were broader than they were high, like goldfish-tanks, whereas we wanted ones which were higher than they were wide. When we finally got tanks of the right shape, the first thing they did was to leak steadily all over the laboratory floor. Applying sealing-compound to them was only one of the last-minute panics which enlivened the production of this programme.

In other cases the problem was to find some way of transmitting a radio signal from the site of the programme to a point where it could be injected into the Post Office landlines which would convey it to Lime Grove and thus to the transmitters. This arose, for instance, in the case of *Trial by Water*. The Hydraulics Lab is not only on low ground beyond the escarpment of the Chilterns but it is surrounded by tall trees. So before any real discussion took place Aubrey Singer telephoned the BBC's planning engineers in London and they got out an ordnance survey map. We told them exactly where we were located by giving them the map reference, and by consulting a similar ordnance survey map at our end. They seemed to think they could find a solution, so we left them to work out whether they could get a line of sight from the lab to some high point where the signal could be collected and bounced on a further stage of its journey towards the nearest cable. In the event it proved possible to do this by dint of bringing in an extending aerial mast. The beam then just cleared the trees, and the engineers found a way to pick up the signal from this transmitter at a point on the top of the Chilterns by dint of placing a receiving aerial on a tower on a disused aerodrome. From here it could be conveyed down and injected into one of the Post Office's landlines.

Many people have asked how the line of light, dancing under the influence of the guitar accompaniment, which forms the background to the opening and closing titles of *Eye on Research*, was contrived.

The device on which it appears is an oscilloscope, a piece of equipment which has appeared in so many *Eye on Research* programmes that viewers must be becoming quite familiar with it. Basically, it is similar to a small television set. A device called an electron-gun fires a stream of electrons at the flat, broad end of a glass tube from which all air has been extracted. The inside of the tube is coated with a material which fluoresces whenever electrons hit it. Where the

electrons hit a brilliant spot of light is produced. A pair of magnetic coils can swing this beam from side to side; another pair can swing it up and down whenever a suitable current is passed through them. The stronger the current the more the beam is deflected.

In a television set, currents (sweep-frequencies) are provided so that the spot of light passes gradually over the entire screen. When it has made one sweep across, it springs back, and the second current moves it downward by one spot-width, so that the next crossing is alongside the first. In this way the whole screen is illuminated, the process being so rapid that the spot gets back to its starting-point before the images of its various positions have faded from the retina of the eye. If the amount of current being fed to the electron-gun is constant, the screen will appear grey or white. If it varies, it will display dark and light patches. It only remains to vary it so that these patches correspond to the lightness and darkness of the picture being transmitted.

In an oscilloscope, however, the current feeding the electron-gun is constant. Further, a first sweep-frequency is applied to one set of coils, causing the spot of light to move from side to side, as before, but no such frequency is applied to the second set. Instead, they receive the signal which is to be measured. For instance, suppose we are sending a radar pulse to the moon, and receiving the echo. We want to know how long the pulse takes for the double journey, so that we can work out the distance (for we know the speed at which radio waves travel).

We arrange for the outgoing pulse to be fed to the coils which control vertical movement: so the oscilloscope shows a little vertical peak at the moment this occurs; similarly, the returning pulse is induced to create a second peak, which will be smaller because the echo is fainter than the original pulse. The longer the journey takes, the farther apart these peaks will be. If we know the speed at which the electron beam is being swept sideways, we can tell from the separation of the peaks the time that has elapsed.

Another use of the oscilloscope can be shown by supposing that we feed to the second pair of coils an alternating current, such as that from the mains. As the current rises the electron beam will be more and more displaced vertically; as it falls, it will return to the centre, and then repeat the performance below the middle position as the current becomes nagative. If we arrange that the sweep-frequency is

the same as the frequency of the current, it will keep retracing the same path. In this way, we can study the *wave-form* of the current. BBC television engineers continuously study the wave-form of their signals in this way. And scientists study, for instance, the rise and fall of voice intensity, as explained in *The Voice of the Machine*.

In the case of the dancing line title background, the sound from the microphone which was recording Fitzroy Colman's guitar-music was fed into just such an oscilloscope as I have described. Each pulse of sound energy thus produces a corresponding deflection of the line. A special circuit alters the frequency of the incoming musical note, so that each note appears as a stationary wave, though its height (amplitude) decreases as the note dies away.

But if the idea is simple, the filming of it was less so. The movement of the camera shutter introduces a complication: each trace is on the screen only momentarily, and is followed by a blank period during which the spot flies straight back to its starting-point. If the shutter is closed at this moment nothing registers on the film. And it took two days in the BBC Engineering Research Department before we had a trace with which Aubrey Singer was satisfied.

As the dancing line trembles to rest and fades from the screen, the first *Eye on Research* begins. . . .

2

Wing in the Future

A visit to a Supersonic wind-tunnel

'ALL out' cried the engineer. And his voice echoed eerily in the vast rounded, concrete tunnel. He stepped quickly through the sloping door and slammed it shut after him: the sound boomed heavily. Behind the vertical slats which seemed to close off one end of the tunnel, the great, many-bladed fan—36 feet in diameter—began to spin, the tips of the blades seeming to sweep the tunnel walls. The air started to waft past our faces, then to roar in our ears, and soon to press on us with almost gale force. The powerful lights we had installed, though heavily sandbagged down, seemed to sway ominously, and I had visions of the lights on the far side of the fan being sucked through it, and hurled, a mass of tangled, heated glass and steel, in our faces.

We were inside the smaller of the two huge wind-tunnels at the Royal Aircraft Establishment's station near Bedford. And we were recording on film the first shot of the first *Eye on Research*.

We had come to this vast estate of strangely-shaped buildings, up a newly-made road and over the brow of a hill: for many conditions, such as availability of water and nearness to an aerodrome, govern the siting of wind-tunnels. And we had come to see how aerodynamicists—as those who study problems of air-flow are called—study aircraft models to provide the data which aircraft designers need.

Aircraft flying faster than the speed of sound create special problems for aircraft designers. This is so chiefly because, at supersonic speeds, 'shock-waves' are set up by parts of the plane. Shock-waves are areas of abrupt change of pressure: those abrupt changes may play havoc with the stability of the aircraft if they should pass near or hit parts of the fuselage. They can also cause the air-flow to become very turbulent. The consequences are especially awkward if they hit the tail surfaces, which control the movements of the plane.

Besides this, supersonic aeroplanes have to be able to fly at slow speeds in order to land and to take off, and this sets the aerodynamicist a big problem, for a plane which is a good shape for high-speed flight may be all wrong for landing.

Three experimental methods are used for developing new designs. The first is to build small-scale models and test them in a wind-tunnel. The second is to make flying models. And the third is to build full-scale aircraft and test them in flight. The first stage is, of course, much more than trial-and-error: complicated calculations are made before ever a model is constructed. And when it is tested in the tunnel very accurate measurements are made of its performance, on the strength of which further calculations are made to account for the measurements. After this a new model may be made to a modified design and tried out in the tunnel: and so on through a series of designs before it is thought worth proceeding to test the model in flight.

Fundamentally, a wind-tunnel is a metal or concrete tunnel in which a model aircraft is suspended. Air is then blown rapidly through the tunnel by a large fan or an air compressor: so, instead of the model moving forward through the air, the air moves backward past the model. Measuring devices record the strains on the model as it is turned into different attitudes relative to the airstream. Modern high-speed wind-tunnels consist of a closed tube round which air is driven continuously by a large fan. A narrowing of the tube increases the air-speed further just before the section in which the model is placed.

At the Royal Aircraft Establishment at Bedford there are a number of wind-tunnels, but two in particular, one dealing with subsonic flight, i.e. flight below the speed of sound, and the other dealing with supersonic flight are of interest. The larger one is designed to achieve speeds up to nearly Mach 3. No need to be alarmed by the system of indicating speed in Mach numbers: Mach 1 represents the speed of sound, Mach 2 is twice the speed of sound, and so on. The reason for this system is that the speed of sound varies according to the temperature of the air. At sea-level, at normal temperature and pressure, the speed of sound in air is about 760 miles an hour. At 80,000 feet it is nearer 660 m.p.h. The aerodynamicist is more interested to know whether a plane is travelling at Mach 1, when shock-waves will begin to develop, than he is in knowing its exact speed over the ground, and so he prefers this notation.

This wind-tunnel, which had only been completed five months before my visit, in November 1957, can, therefore, test planes which will fly in reality at speeds of about 2,200 miles an hour at sea-level. But to achieve a wind-speed of this order involves an enormous increase in the amount of effort; whereas the smaller tunnel contains a fan driven by a 3,500 h.p. motor, the big tunnel itself requires motors to drive the fan totalling 88,000 h.p. It is also much bigger. The compressors are the largest of their kind in Europe.

To provide the power to drive these motors as much electricity is required as would be consumed by a small town, while the coolers which take the heat out are also of giant size.

To force the air to attain such enormous speeds not one fan but a series of compressors is necessary, and the air in the tunnel is under pressure when the tunnel is working. This pressure produces a reaction in the tunnel itself, amounting to 1,500 tons, and mighty struts are provided to absorb it. Plate 2 will give an impression of the layout.

Walking down the corridor leading to the control-room, I did not have a very great impression of size. It was only when we left the control-room and were making our way up to the Schlieren chamber (about which more in a moment) that I suddenly caught through a doorway a glimpse of a huge curving surface, the underside of part of the tunnel. I was so impressed I particularly asked Aubrey to find a way of including this glimpse in the programme, and with the aid of arc-lights and some awkward juggling of the available cameras he did so: several people commented afterwards on the dramatic effect of the sudden revelation of the size of the construction.

The energy supplied by these motors does not vanish into thin air —or rather, it does in a literal sense: the air becomes heated. This, of course, affects its aerodynamic qualities and it is therefore necessary to cool it to normal temperature again; thus, in effect, this wind-tunnel puts 88,000 h.p. of energy into the air and takes it out again a few feet later: a wasteful process but one which no one knows how to avoid.

Furthermore, the air must be completely dry. The air, therefore, circulates round and round within a closed tube and no leakage into it of damp air from outside can be permitted. The amount of water which can be tolerated is no more than 0·02%. To seal a tube of this size is a major problem: the shell is 47 feet in diameter and some hundreds of yards long if the full course round the ring-shaped path is

measured. The heat developed and the pressure of the air cause it to increase in size by some 5 inches when it is at work.

The tube narrows just before it comes to the experimental section, thus causing the air to travel even faster and this is how the supersonic speed is attained. The throat through which the air rushes is about 8 feet across and the models which are placed in it are therefore normally something like 1 or 2 feet across. To control the airspeed, the shape of the whole working section is altered, by a series of enormous hydraulic jacks, which can be raised and lowered so as to raise or lower the floor of the wind-tunnel—or rather, that section just before the experimental area.

The Royal Aircraft Establishment put together a special model for the *Eye on Research* programme, building it largely out of components which they already had available: for instance, the wing belonged to a model of the Fairey Delta 2. We then showed it being tested both in the low-speed tunnel, where its behaviour at landing and take-off speeds could be studied, and in the high-speed tunnel where its behaviour at supersonic speeds could be observed. Very appropriately, the draughtsmen christened this design 'The World Scanner'.

The model built for the programme was of a design which would seem unusual by the standards of the planes we know now. It was a four-engined plane with the delta-wing shape which some of the RAF's latest high-speed planes have. The engines, however, had not been put in the wings, as we usually see them, but two in the tail and one on each wing-tip: the idea here was to avoid the noise of the engine disturbing the passengers and also to make it easier for the ground-crews to maintain them. The aerodynamic shape was suitable for a maximum cruising speed of Mach 1·6, or about 1,200 miles an hour.

Mr Philip Hufton, one of the staff of the Establishment, took me round. We decided to open the story in the low-speed tunnel. So accurately is this fan made, in order to get the maximum purchase on the air, that its tips, travelling at a very high speed, pass within a fraction of an inch of the edge of the cage. If any expansion or distortion occurs the end of the tip is immediately worn off. No one must remain in the tunnel when the airstream is going at full speed, though one can enter the experimental section through a door, under certain precautions. The working section measures 9 feet by 13 feet, and can take models of up to 9 or 10 feet wingspan.

As I entered the experimental section from the control-room I noticed that the speed of the air increased very rapidly, as the width of the section narrows. I was standing in a comparatively mild breeze at the end where the airstream enters. I moved a few paces downstream and found myself in a gale.

Scientists observe the experimental section through a glass window from a control-room in which the measurements being made on the model are automatically recorded. From here the position of the model can be changed by remote control; it can be put into the kind of attitude which would represent a climb, a dive, a turn, and so on, while small pressure-gauges, embedded in the surface of the model, and recording electrically, send messages out to the control-room instruments.

However, it is also possible to study the path of the air round the model by more direct methods. Mr Hufton showed me how smoke can be created by the use of titanium chloride: the way in which this flows over the wings can be noted. The upper surface of the wind is under reduced pressure, for this is how an aeroplane gets its lift—the entering edge of the wing forces the airstream upwards so as to create a slight vacuum over the wing. Underneath the wing it is at pressure and part of the lift comes this way. Consequently, there is a tendency for air to flow from the region of high pressure to the region of low pressure and this produces vortices or whirlpools. These whirlpools can be distinctly seen when this chemical smoke is released in front of the plane and when the tunnel is lit by a thin slice of light.

Having examined the way in which the air flowed over the model in its normal attitude, the next step was to reduce the angle at which the aircraft is flying, as if it were levelling after taking off, and it could then be seen immediately that the vortices became much less and so did the disturbances behind the tail. In other words, any difficulties the design would meet would be those immediately on landing and take-off, rather than at the rather higher speed following take-off, or during the approach itself.

An aeroplane, of course, must fly in balance and for this to occur the lift on it must act at the same point as the weight, to counterbalance it. Obviously, if the lift acts ahead of the weight the aeroplane's nose will tend to turn up. The pilot can try and correct this by adjusting his controls but his power to do this is limited and the designer must be sure that the aeroplane is pretty well in balance.

Though the *World Scanner* was reasonably satisfactory at low speeds there was not much margin at the rear, where turbulence was occurring at take-off. Supposing that the study of its characteristics when flying at high speeds should necessitate any changes in the positions of the tailplane, the fin and the rudder, this might have serious consequences at low speeds. In this case further low-speed tunnel tests would have to be done to make sure that the turbulence had not become serious.

The next step was to move to the high-speed tunnel for tests at supersonic speeds. In this big tunnel the working section is somewhat smaller, being 8 feet by 8 feet in cross section, but it can take models up to 6 feet wing-span. To increase the speed of the air, the tunnel gradually narrows as it approaches the experimental section. The exact air-speed is regulated by moving the top and bottom walls of this 'throat' so as to increase or reduce the narrowing. The floor and ceiling are made of flexible steel held in position by a series of jacks (as can be seen in Plate 2. The jacks are driven by hydraulic motors, each of which is in turn controlled by punched tape. The system moves the walls into the required position automatically as soon as the man in charge of the test has selected the Mach number he wants and has pressed the start button. The movement of each wall is 2 feet 11 inches, but it can be moved by as little as 0.0025 in. (or half this, in the case of the nine downstream jacks) giving a total of 14,000 steps fro the complete travel.

The air pressure in this converging section and in the working section is measured at many points and displayed in the observation-room on rows of manometers (pressure gauges). This installation required over 40,000 feet of small-diameter copper tubing.

In the high-speed tunnel, the model is supported by a tapered rod, known to aerodynamicists as a 'sting' because it projects into the tunnel horizontally and looks rather like a bee's sting. This, of course, is so that it shall disturb the airflow as little as possible. The plane's behaviour can be seen by closed-circuit industrial television, while the stressing imposed on it can be studied by means of electrical signals from the strain-gauges within it. These strain-gauges can record loads of up to 1½ tons per square foot. Thirdly, a visual picture of what the airstream is doing can be obtained by what is called a Schlieren optical system. In this system a parallel beam of light travels across the airstream: if any changes occur in the density of the air,

this causes light and dark shadows on the screen on which the light falls. You have seen something similar if you have noticed the wavering effect of hot air rising from a radiator or other hot surface. With this device shock-waves—which are density changes—show up very clearly.

On the far side of the tunnel from the control-room, therefore, is the Schlieren chamber, where the shock-waves are observed. The picture thus obtained is 'piped' down to the control-room by a sort of long periscope.

You may be surprised that the strain-gauges should record pressures as high as 1½ tons a square foot but the pressures which air exerts on models when travelling at speeds around 2,000 miles an hour are remarkably high. The models themselves are machined out of solid steel by extremely elaborate machine-tools, to an accuracy of 1½ thousandths of an inch. The trailing edges of the wings are cut so accurately that it is possible to cut one's finger on them: in fact, one of the television camera-crew, carelessly knocking his ankle against one of the models during rehearsal, actually did cut himself.

When the airstream is run up to speed the aircraft is tilted, rolled or caused to point first to left and then to right—that is, to yaw. The readings on the strain-gauges are recorded on sheets of paper by moving pens and so draw their own graph.

The angle of the shock-waves changes steadily as the speed increases. In the case of our model, the *World Scanner*, the Schlieren showed that shocks from the engine exits—for the stream of hot air leaving the jets tends to set up a shock-wave—would strike across the fin and the rudder at somewhere near Mach 1·6. Raising the speed to Mach 1·8 showed that quite strong shocks began to originate at the point at which the wing-root joined the body. Furthermore, when the aircraft was yawed there seemed to be quite violent changes of the pattern of air-flow into the engine intakes. Shock-waves could be seen appearing and disappearing.

The fundamental research which has been done at the National Physical Laboratory, the Royal Aircraft Establishment, and other places, about the effect of shock-waves striking surfaces, would lead one to expect serious results. The tendency of the plane to move about, recorded by the instruments, was no doubt due to the shock-waves striking the tail surfaces. The solution would seem to be to lengthen the body and put the fin and rudder farther back. In this case the shock-waves from the engines would only strike them at a

higher Mach number. An additional reason for not allowing this plane to fly as fast as Mach 1·8, however, would be constituted by the shock-waves from the wing-roots. So it would seem that this design would be satisfactory if the designer's intention was to fit it with engines which would at no time make it fly much faster than Mach 1·6. Even so it might be unsafe if the pilot should put it into a dive that would carry it up to a speed of Mach 1·8.

Of course the results obtained on the model cannot be applied without further consideration to real aircraft. First the designer must ask himself whether the effects shown on the model will really happen on the full-size plane. To begin with, the model isn't completely representative of a full-sized plane because it does not have real engines and the flow of air from the jet exits is therefore not simulated. Furthermore, models are not quite the same as the full-size thing because one cannot scale down the characteristics of the air itself. It is possible to make allowances and calculation for what is called the 'scale-effect' but you can never be entirely sure that these allowances have been made quite correctly. To try this, one must build a full-size plane, but one cannot do this until one is reasonably certain that the pilot will be able to control it.

Finally, there was the fact that the low-speed tests had shown that the tail position of this plane was rather touchy, and hence that if the tail-unit was moved farther back to avoid the shock-waves it would probably get into a bad position which would cause difficulties in air-flow when the plane was trying to land or take off. The chief designer would therefore have a pretty difficult time to make a compromise between these two lots of needs.

To sum up, one might say that the low-speed tests of *World Scanner I* were reasonably satisfactory but that the high-speed tests were not, and various changes of design would have to be tried to resolve the difficulties.

The chief designer, of course, has complete responsibility for overall design. The aerodynamicist is a specialist who points out where compromise may be necessary. The chief designer has to think about the demands which will be put upon the aircraft, what load it will have to carry, how much fuel, how fast it will be expected to go. The aerodynamicist helps him with the basic aerodynamic information he needs to do his job, and it must be extremely rare that a design is ever found to be right the first time.

Today the aerodynamicist is just as interested in missiles as he is in aeroplanes. With missiles similar problems arise even though the control is now done automatically, or by radio, radar and so forth, and not by a pilot sitting in the missile. However, the speed range of missiles is beginning to extend beyond that covered by this tunnel and the RAE has in construction at Bedford, and nearly complete, another tunnel which will enable them to experiment on speeds up to Mach 5, or say 4,000 miles an hour. This would cover most needs short of the so-called ballistic missile and the inter-planetary devices.

You might think that out in space, where there is no air, the aerodynamicist would have no part to play, but of course even interplanetary vehicles and Sputniks have to go through continually thinner air to get up to their orbit. They may have to re-enter the air again: and the speed of re-entry is likely to be extremely high. The problem of devising wind-tunnels which will make it possible to carry out tests at speeds of perhaps 20,000 miles an hour is a major enterprise. The Royal Aircraft Establishment is working hard on this at Farnborough.

And now from problems of air-flow to problems of water-flow.

3

Trial by Water

How scientists build scale model rivers and harbours to explore problems of flooding and silting-up.

In Oxfordshire, not far from the little market town of Wallingford and close by the River Thames, stands an enormous building which one might take for an aeroplane hangar. Near it lies an old mansion and beyond that a great open tank ending in a shelving beach of sand, against which waves beat continuously: this is the headquarters of the Hydraulics Research Station of the Department of Scientific and Industrial Research.

Entering the hangar-like building one has the feeling of entering a particularly large film studio, for only two pillars disturb the vast open space of floor. This building is 300 feet long and 200 feet wide and is to be extended to three times the size when funds permit.

I had been to visit the hydraulics laboratory in 1956 in connection with inquiries I was making about the Colombo Plan, for down at Wallingford they have been working on silting problems in the Karnafuli River in Pakistan, and it occurred to me immediately that this would be spectacular material for a television programme.

Inside the vast experimental hall are models in different stages of construction of various rivers, several of them a couple of hundred feet long, with water flowing smoothly along the winding course of the river and tides slowly flowing in from the seaward end and receding again.

To show these fascinating models presented a production problem, for to appreciate them one must look down upon them. Aubrey Singer therefore decided to invest a good part of his available budget in hiring a large camera-crane on which the camera could be taken up to a considerable height so as to give a long-shot impression of each model and then rapidly swing down to a point right over it to

see the details of what was occurring. For while a human being can walk on certain of the models without damaging them, it would not have been possible to have wheeled a camera trolley over them in this way, particularly as the models stand some feet off the ground.

The work of this laboratory covers not only the silting-up of rivers and harbours but such matters as the control of flooding, how to stop coastal erosion and any problem arising from the natural movement of water. The sort of thing which can be done in this field is well illustrated by a problem which arose in Trinidad, where a dam is planned. To carry off excess water when the reservoir was full, a spillway had to be constructed, but, owing to some high ground, the lower part of the spillway had to take a sharp right-hand turn. Experiments in the model showed that the flow in the lower part of the spillway followed a circular path, resulting in an uneven discharge of water from it, which threatened to undermine the structure. To have built the spillway on an easier curve would have meant blasting away thousands of tons of hard rock, and would have been prohibitively expensive.

The Hydraulics Lab was therefore called in, and the spillway was reconstructed in miniature at Wallingford. Fergus Allen showed me this model: as the water was released, I could see how it boiled round and round. Ping-pong balls were dropped into the water to show how it actually moved backwards at one point. Experiments soon showed that the unwanted turbulence could quite easily be stopped by putting in two small wooden fin-like walls in the straight part of the spillway; this caused the water to flow in a smooth stream and not to rotate. By taking the fins out of the model the re-creation of the whirlpool and the rise in level of the water could easily be seen.

Of course the trick is knowing just where to put the fins, and how big to make them. When this has been discovered they can be built in concrete on the real dam. To test them in a model is, of course, much cheaper than to build them and rebuild them on the full-scale dam.

This is a fairly simple problem in hydraulics, chiefly because the channel in which the water was flowing is fixed. The work of the hydraulics expert becomes much more difficult when a channel silts up or shifts about as it does in a river or harbour. The lab is working at this time on a major siltation problem for the Mersey Docks and Harbour Board. The River Mersey runs into the sea between Liverpool and Birkenhead, which together make up the largest and most

authority on hydraulics, but the directorship has recently passed to a much younger man, Fergus Allen. He took me round and explained to me how these models are built up so as to be exact in every detail.

The first step, of course, is to measure up the actual river-bed and the rate of flow of water and tides. To begin the model we start, he said, with a waterproof flooring and then build a low brick wall around the area we are going to use, which we also waterproof. To model the river-bed we start by cutting out cardboard templates which show the profile, or shape of the river-bed, at every so many feet. These templates are then set in the bottom of the waterproofed tank at the appropriate intervals, after which modellers with sand build the sand up to the heights indicated by the various templates.

When the river-bed has been modelled in this way, fresh water has to be fed in at the correct rate at the inland end. A system of pumps and sluices is built for this purpose and as one walks round the hall, the musical rushing of water from the many sluices can be heard in every direction. (The whole hall, incidentally, is heated from the roof by radiant heating elements so that a constant temperature is maintained.)

But at the seaward end of the model the incoming water has to be tidal. Now tides are not as simple as they sound—not only do they shrink down to neap tides and then grow in range to spring tides, but the water does not come in at an absolutely even rate. Hydraulics engineers, therefore, say that a tide has a 'profile'. Profiles vary because a narrow channel will hold the water up for a bit, while in a broad marshy area it will spread out sideways and slow down its forward advance. Tide-making machines of various kinds, therefore, have been devised to regulate the flow appropriately. There are two main types—'displacement' and 'weir' types; both are electrically controlled.

Since salt water will tend to work its way under less dense water it may be necessary to feed salt into it at a predetermined rate, and a gadget for this purpose has had to be devised.

When the model is functioning, it is necessary to check that it is doing exactly what the river does—so a series of tides are run through. Tides, of course, normally take twelve hours but on these models they can be run through much more quickly—say, in nine minutes. As this is done, the water-flow begins to modify the position of the

river-bed in the model. Since we know from charts just how the Mersey has changed its bed during the past century, one can see whether the model is repeating the history of the real river.

One must also check whether the water is rising and falling on the model, as it should do to match the real thing, and delicate instruments have been devised at Wallingford to do this. A few inches above the water, Allen showed me, stands a little black box from which a probe projects towards the water. This probe is automatically maintained with its tip immersed a hundredth of an inch or so in the water and the motor which causes the probe to withdraw or advance as the water rises and falls, at the same time makes a record of this movement on a roll of paper.

In the same way the speed of the water in the model must be measured. Just as in measuring the speed of real rivers, the water is made to drive a kind of propeller—but for the model this propeller must be extremely small and finely mounted; less than half an inch in diameter, it could be contained in a pill-box (see Plate 3).

The technical staff at Wallingford have also invented a quick and accurate way of measuring the shape of the bed so that shifts in its shape can be studied. This, too, consists of a probe which travels across the bed of the model river on an overhead track. The probe keeps itself always a quarter of an inch from the sand on the bottom: when it senses the sand approaching it withdraws itself. This depends upon the fact that the 'impedance' between two electrodes immersed in water alerts when they approach the bed. ('Impedance is a technical term for a particular kind of electrical resistance.) When it comes to a steep place, so that the probe shall have time to withdraw quickly without bumping into the small hillock of sand, the rate of traverse automatically slows down. The signals from this device draw out the profile on graph paper.

The Wallingford staff expect to be working on the Mersey model for four or five years and when they are satisfied that it exactly represents the real river they can start trying to find ways of reducing the silting.

Though their work is partly trial-and-error, hydraulics engineers are steadily building up a fundamental knowledge of how sand and water move and at Wallingford there has been constructed for this purpose what is called a 'wind-wave flume'. This consists of a channel of water, 4 feet high and 4 feet across and 185 feet long: it is

in a long, low building with a semi-circular roof. At one end is a wave-producing device. It is rather eerie to walk along this dark tube with the waves of water just by one's ear, rushing to and fro. Windows in the side of the flume make it possible to observe the movement of the water. The movement of the water can be studied by dropping a dye in and observing what happens through the glass panels. Experiment shows that the direction in which the dye moves depends both upon the height of the wave and the depth of water. Later a sandy bottom may be introduced.

A thing which struck me as particularly interesting: when a rubber ball was placed on the bottom, it slowly advanced in the opposite direction to the movement of the waves. Though it moved a little forward with each wave, it moved still farther back during the period of low pressure after the wave had passed.

The walls of this flume have to be kept dead flat within a twentieth of an inch to make sure that the wave-motion is not disturbed by eddying.

The Wallingford people propose to improve this model by installing a large fan which will draw or blow air over the water and thus modify the waves as would happen if there were offshore or inshore winds. Finally, Fergus Allen told me, they propose to imitate the effects of a cross-tidal current which causes waves to approach the shore diagonally—though this will be done in a different tank.

The big tank which I had seen outside also serves to demonstrate these diagonally-approaching waves and to study how to stop the shifting of sand along the coast under their impact.

You might think that work of this kind would be of direct interest only to public authorities, river conservancy boards and bodies of that kind: but sometimes it has the most obvious and direct benefits to the man in the street, or rather the man in the boat.

One of the problems on which the laboratory staff were working when we went there provides an instance of this. One of their models —as a matter of fact the very first you see as you enter the great hangar—is a most realistic model of the little fishing harbour of Eyemouth, a town just north of the border between England and Scotland and a few miles from Berwick-on-Tweed. Fishing is the main industry for the people of Eyemouth, and now that living is being threatened by the action of the sea, which is silting up the entrance to the harbour.

We therefore decided to send film cameras up to Eyemouth and there Jameson Clark, one of the BBC's Scottish interviewers, asked the fishermen and the Provost to explain the alarming situation which is developing—a matter of life and death, as one old fisherman, with pardonable exaggeration, described it.

The problem started as long ago as 1907. The boats now sometimes have to lie in the bay for seven or eight hours before there is enough water for them to get into the inner harbour. The harbour commissioners have been removing some 2,500 tons of sand per year; when the tide is down they take a bulldozer out on the sandbank and push the sand up to the quay wall where they have an excavator and five or six lorries standing ready. The excavator fills the lorries and the lorries take the sand away and dump it over the cliff. For a small community, this amounts to a heavy expense.

Silting takes place when the wind is in the north-east: the waves come in, carrying the sand with them. This occurs mostly in the winter and usually there are two or three gales from the north-east each season. If the boats are late getting in, then they may miss the market and consequently the fishermen will not get as good a price for their fish.

Three hundred miles away in Wallingford, where probably none of the Eyemouth fishermen have ever been, there is a team of men studying their problem on a model of Eyemouth Harbour on a scale of 1 in 14 feet—a problem far smaller than the Mersey's but in principle much the same. On this relatively large model a wave would be about three inches in height.

The model matches the real thing extremely well. It produces a sandbank very similar to that at Eyemouth although it does take rather longer—in terms of tides—to do so.

The next step was to find out where this sand was coming from. One way this was done was by using radioactive sand-particles. These were dropped into the water, and tides were run until the sandbank had been built up. Then a Geiger counter was employed to detect where the radioactive sand had got to. In this way the sand movements within the bay, as the tide went in and out, could be calculated. Incidentally, a similar technique had been used in the Thames, to trace mud movements.

Having charted the problem, the question of a solution could be tackled. Three remedies had been tried: the first was to extend the

model pier by adding a breakwater, and to see what happened to the tides. A second possibility was to create a place where the water could be held back at high tide and then let out in a rush to see if this would have the effect of washing the sand away. When I visited Wallingford they were working on a third plan which involved constructing a new entrance. This, of course, would be the most costly of the three solutions and it was a question of seeing whether the results achieved would be so much better as to justify the additional cost. Eight schemes were tested eventually.

At the same time it was necessary to see whether such modifications might create navigation problems. This is done by means of trials with a radio-controlled model trawler. This was put into the water for me and chugged happily into harbour.

Another of the most interesting river models reproduces about five and a half miles of the Trent valley, where it is crossed by the new London–York motorway between Nottingham and Derby. The valley spreads out in a shallow basin at this point, and in winter flood water ranges wide over the neighbouring fields. To avoid the floods the road is carried across this area on an embankment and a viaduct. This creates the problem of how these new works will affect the flow of the water and its ability to get away as the floods subside. To put the whole road on arches would be enormously expensive. The question which the authorities wanted to solve, therefore, was: how many arches should be provided and where should they be placed? If too few were provided, the flood water might pile up in a great lake, causing even greater damage to the farmers' lands and crops than before. It might undermine the embankment on which the road is to run. And it might pour so rapidly through the openings provided as to scour away the earth and weaken them.

The solution was to construct a model of the whole valley, placing the road on arches for the whole distance. And then to block various sections of arches in turn and see what happened. But to achieve this effect it was, of course, necessary not only to feed water into one end of the model to simulate the river, but to make sure that when the rate of flow was increased, the water would gradually back up and flood, covering just the same areas as it does in real life.(see Plate 4).

This the hydraulics experts managed to do, and their efforts have, it is estimated, saved the Ministry of Transport, and thus the taxpayer, about £800,000.

Flooding is also a problem in the tidal reaches of the Trent, and here the catchment authority has commissioned the building of a model of some sixty miles of the river's course. The idea is to find the cheapest and most effective method of controlling the flooding. What would be the best positions in which to place flood-retaining walls? Could a by-pass channel be cut which would lead the water past the danger area? This model aroused the particular interest of Her Majesty the Queen when she visited the Hydraulics Research Laboratory. For her benefit it was fitted out with miniature houses, where the various small towns are situated, and we made use of the same idea. As the camera soared along the course of the river on its giant crane, the viewer had the impression of flying along the course of the river in a swift jet aircraft. What you would not have seen from an aircraft, however, was the red line on the model marking the extent of the great 1947 floods.

Scientific accuracy compels me to add that, as in most of these models, the vertical scale is larger than the horizontal, so that if the houses had been constructed accurately to scale, they would have seemed remarkably tall and thin.

These last two models (like the Trinidad dam) are what is called 'fixed-bed' models because they are constructed of plaster and no attempt is made to imitate or study the gradual shifting of the river-bed, as is necessary at Eyemouth and with the Mersey and the Karnafuli. The term 'fixed-bed' is used in contrast with 'mobile-bed'—mobile-bed models being built in sand.

In the course of the half-hour to which the programme was limited we had no time to show anything of the work which goes on in the outside tanks of the establishment. Much work is done, for instance, on coastal erosion, and I saw an experiment being made to prevent large merchantmen bumping up against the pier in a certain Australian harbour. In mooring the model vessel, the strength and elasticity of the mooring ropes must be imitated, and I was charmed to see, in a near-by workshop, three spools of nylon thread of different sizes, labelled: 2-in. rope, 4-in. rope, 6-in. rope.

The work on the problems of particular rivers or coastal areas is less important in the long run then the building up of a body of generalized knowledge about how water behaves in different sets of circumstances. Hydraulics has advanced less than aerodynamics in this respect, but out of the many particular studies a front of this

basic knowledge is emerging. From it general principles can be deduced, and it is the establishment of these principles that is the real task of any scientific discipline.

With this splendid new laboratory, now twelve years old, Britain is forging ahead in the field of hydraulics research.

4

The Dividing Line

How scientists are using a scratched mirror to bring about a new industrial revolution.

THOUGH bad workmen may blame their tools, it is also true that good workmen take care to equip themselves with the best tools. They may not have many, but those they have are good. Scientists likewise depend on their tools, and I have been struck, in my wanderings to different laboratories, by the way in which the whole progress of science depends upon the availability of tools. Later I shall describe how the development of the electron-microscope opened up the exploration of the virus; indeed it transformed the study of the cells of the body and of plants, also. Following the creation of a new tool, there is a period of lag in which the price is brought down to the point at which many laboratories can afford it. This is now happening with the electron-microscope: the number of laboratories possessing one increases every year.

Much the same had happened with another basic tool of science, the spectrometer or spectroscope. This enables scientists to identify what elements are present in any material which can be made to glow, whether by heating it or passing an electric discharge through it. It can therefore be used to identify the elements present in a distant star, and with absolute certainty. These, naturally, cannot be examined by any more direct means. Not only this, it also provides the scientists with information about how the atoms in the element being examined are arranged. It is therefore a tool of wide scientific importance. For instance, in one of its modern forms, it is used by the oil-refining industry, to analyse the component substances in various oils.

The core of the spectroscope is an object known as a 'diffraction grating' and unfortunately, until recently, this was costly and

difficult to produce. It consists of an enormous number of accurately-ruled lines—they used to be ruled on glass or metal—sometimes as many as 30,000 to the inch. There were only one or two machines in the world capable of ruling such gratings. The process was slow, and any sudden vibration or jar might cause an irregularity in the ruling which would ruin the whole grating.

At the National Physical Laboratory, at Teddington, there was, at the time of our television programme, a ruling engine known as the Blytheswood machine, made some seventy years ago, which was still in operation. (Since then it has been retired and will soon be seen in the Science Museum.) It ruled lines on a polished aluminium surface with a diamond tool. With each stroke of the diamond the surface being ruled was moved on by one fifteen-thousandth of an inch, by means of a screwed rod and a ratchet which turned it once per stroke.

Ruled line-by-line in this way, even a small grating, less than an inch square, took a hundred hours to rule. But many of the gratings thus ruled proved on examination to be defective, owing to vibration or other reasons. During the whole period 1907–45—that is, thirty-eight years—the Blytheswood machine produced only 200 usable gratings. This explains why gratings were costly and spectroscopes embodying them hard to get.

Though the Blytheswood machine has gone out of service it has contributed many of the gratings on which the science of spectrometry was developed. Without machines of this kind we should not have built up the fund of knowledge which engineers draw on to construct the atomic power stations of today.

Until recently there were only a few hundred gratings in the whole world. The ruling of these gratings is probably the most difficult manual operation in the whole of applied physics. While the machine is working nobody can be in the room and it chugs away by itself under a large cover. Even so, the grating are liable to exhibit imperfections and these occur particularly if the machine is started and stopped or reversed.

For the grating to be perfect the lines must be spaced evenly, which means that they must be placed within a few millionths of an inch and must be perfectly straight. Consequently, even slight changes of temperature or vibration during the ruling can spoil a grating. In particular, the cutting of the thread which advances the grating in

such a machine must be perfect. How are all these requirements to be achieved?

That, then, was the question; how to find a quicker, and if possible more accurate, method of producing such gratings. British scientists have recently solved the problem. Starting from a suggestion made by Sir Thomas Merton, formerly Professor of Spectroscopy at Oxford, the Light Division of the National Physical Laboratory at Teddington developed a completely new technique for producing them. Once these new gratings had been developed, they proved to have applications on a much wider scale than simply for use in spectroscopes.

This explains why, one winter's day, I found myself visiting the National Physical Laboratory to see Dr Sayce, the head of the Light Division. The National Physical Laboratory covers a sixty-acre corner of Bushy Park, and its many buildings present a wide variety of styles, from unattractive single-story huts to the charming red brick of Bushy House, a dignified one-time royal residence, in which the Laboratory started sixty years ago.

From the window of the Light Division Building one can see—appropriately enough—a small apple tree. This may seem a curious thing to find in a scientific laboratory devoted to physics, but in fact it is quite appropriate. It is direct descendant of the tree from which an apple fell in the autumn of 1666, and which gave Sir Isaac Newton the idea of his great generalization about gravity. Newton, however, also made basic discoveries about the nature of light, and from these discoveries the spectroscope itself arose. He passed light through a wedge of glass, or prism, and found that it was made up of a blend of brilliant colours: all the colours of the rainbow or spectrum. From this he won a great insight into the connection between light and matter.

The prism used to be the central feature of the spectroscope. At this point by way of background to the story of the diffraction grating, I must explain how the spectroscope works.

We consider light as consisting of vibrations in the ether, and these vibrations occur over a range of possible frequencies of vibration. We may equally say that light may consist of many different wavelengths, for every rate of vibration has its own wavelength. The shortest wavelength visible to the human eye appears to us as blue, and the longest as red, with the other colours of the spectrum in

between. There are also shorter wavelengths than blue—the so-called 'ultra-violet' light; and longer wavelengths than red—the so-called 'infra-red'.

Whereas white light consists of a jumble of all possible wavelengths, glowing gases and vapours give out light of a different sort, made up of certain definite wavelengths and no others. Thus any chemical element, when made to glow by heating or by an electrical discharge, gives out a kind of signature tune of wavelengths which can readily be recognized and which identifies it as accurately as a finger-print.

The spectroscope is a device for doing just this. The light from the substance being examined is fanned out by a prism, and a small viewing tube is swung round on a graduated scale, from which a reading can be taken every time a particular wavelength is seen to be emitted.

A more effective way of splitting up the light than by using a prism is to substitute for it a 'diffraction grating', such as I have already mentioned. The simple experiment of shining light through such a grating will show that it does in fact break light up into a spectrum of colours, just like a prism does. The principle has been known for 150 years. (The reason it has this effect is rather complex and need not worry us here.)

After considering the problem of how diffraction gratings can be made more accurately, Sir Thomas Merton, the former professor of spectroscopy at Oxford, made two suggestions: first, he said, could we not find a method of ruling the groove continuously, and thus avoid the stroke forwards and backwards, which tends to introduce error? Could we not cut a fine screw-thread on a metal cylinder which would turn continuously under a diamond, and then find some way of copying this upon a flat surface?

The second suggestion concerned the cutting of the master-thread which would drive the lathe on which such a rod would be cut. To achieve this he suggested what has been called the 'Merton Nut' but what he called an integrating nut. First, a rod with a screw-thread is made as accurately as possible. On it is mounted a saddle on which is fixed a cutting-diamond. As the screwed rod turns, the saddle travels forward, and with it the diamond which cuts a second thread on a further rod: this is, basically, what engineers call a 'chasing lathe'.

Now, Merton's idea was that the nut, running along the first

thread, should consist of three strips of pith, pressed firmly against the primary thread by springs. The pith may be spread over as many as 30,000 threads, hence, as it moves, the errors in any individual bit of thread tend to be averaged out; when it moves, it moves according to the averaged thrust of the 30,000 threads. Consequently a more perfect thread is cut on the secondary bar. It is even possible to use this more perfect thread to cut a still more perfect thread, by using the secondary bar as the primary bar on a further chasing lathe.

Now we come to the third problem, which is that of somehow turning the cylindrical rod into a flat grating. This is done by spreading round it a thin plastic (polystyrene) coating which will form a duplicate 'negative' image of the thread. After it has hardened, it is removed by cutting along the cylinder thus formed and is spread out flat. From this 'negative' copy, known as a 'pellicle', 'positives' can be made, much as gramophone records are made from a negative 'matrix', prepared from the master record. On this copy grooves in the original will appear as ridges, and ridges in the original will appear as grooves. This is why it is called a 'negative' copy.

After the pellicle has been removed from the cylinder, it is opened out and laid out on a piece of absolutely flat gelatine: the gelatine takes the impress as it dries and it can then be hardened by ultra-violet light and by baking. From this gelatine 'master-grating' further copies may be made by casting in a polyester resin.

There are, of course, many other precautions to take when a perfect grating is to be cut. For instance, one must see that the cutting edge is undamaged and that the diamond has been properly edged.

To give some idea of what is implied by an attempt to rule 30,000 lines to the inch one can say that this means ruling about one and a half miles of scratch for each inch of rod. It can be seen, therefore, that the wear on the diamond is a factor to be considered. On the rod as a whole, when the longest grating which can now be made is being constructed, the line rule would stretch, if straightened out, from London to Doncaster.

After the war there was an increasing demand for gratings and a great shortage of them developed—a famine, Sayce called it. To make them tied up skilled staff. These new methods have reduced the cost of a grating from £200 or so to about £20 and, what is more important, had made it possible to produce them in quantity because once a master grating has been made, a number of copies can be taken from

it without further ruling, in just the same way that copies are made from a gramophone matrix or photo negative. In consequence, diffraction grating spectrometers, which were few and far between before the war, are now appearing in labs all over the world and even in those not too lavishly supplied with funds.

The spectrograph can also be made to work with the invisible vibrations in the ultra-violet and infra-red, at either end of the light spectrum. Indeed, the principle has been adapted for other forms of radiation such as X-rays. But in all these cases, of course, photographic plates must be used to record the image, since it is invisible to the eye. Infra-red spectrometry is extremely useful in, for instance, the oil industry, where it is used to analyse the component substances in various oils.

But this is only the first part of the story, for when it had been realized that these gratings could be produced cheaply other applications were soon devised. The most immediately interesting, which is already in use, is its application to automatic machine-tools. With the progress of automation machine-tools controlled by magnetic tapes are being constructed. The tapes regulate the movement of the cutting point in all three directions, and such machines will produce bits of metal of complicated profiles without further attention again and again. But if they are to work accurately, they must contain a standard of measurement. When the magnetic tape instructs the machine to advance its cutters by ·025 of an inch, they must advance that distance and no more. The diffraction grating makes it possible to build into these machines a form of measuring rod which the machine itself can read.

This is how it is done. If you consider a foot-rule it is, after all, only a series of parallel lines—a foot-rule marked in tenths of an inch has 119 parallel markings (if we assume that the two end markings consist of the end of the rule itself.) Now a diffraction grating also consists of parallel lines and is thus a kind of ruler, the difference being that the markings on a foot-rule are numbered, so we can count them easily, but the markings on a diffraction grating are not. The problem was therefore to find something equivalent to a way of marking or counting them. One could rule a long grating to correspond to the foot-rule and attach it to a cutting tool so that the grating moved along as the cutter moved, but how could the passage of these finely-spaced rulings, invisible to the eye, be detected?

To do this recourse was made to a phenomenon known as the 'Moiré Fringe', from its appearance, which somewhat resembles moiré ribbon. To explain this effect on television we used two pieces of glass, printed with parallel black lines, so as to resemble much-enlarged diffraction gratings. Now, if one piece of glass is placed on the other in such a way that the lines are not parallel but criss-cross, it will be seen that a fringe, or line of light, runs across the glass at an angle which divides the angle between the two sets of lines (see Fig. 1). This line is composed of a series of diamond-shaped openings,

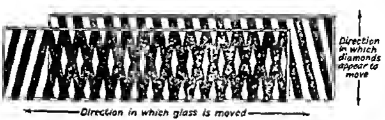

FIG. 1.—'Moiré fringes.' If slanting lines are painted on a piece of glass, and this is laid over another piece of glass on which are painted lines sloping the other way, a series of rows of white (or clear) diamonds is seen. When the lines are narrow, and closely-spaced, the rows of diamonds resemble horizontal lines. If the upper piece of glass is slid sideways over the lower one, these horizontal lines move up and down. They move by an amount equal to the distance between two rows, when the glass is moved sideways by the distance between two lines. This vertical movement is much larger than the horizontal one and easier to measure. The whole arrangement forms a sort of 'movement magnifier'.

where the black lines on neither sheet of glass block out the light. If one sheet of glass is moved *sideways* over the other, this line of diamonds moves *upwards* or *downwards*. When the glass sheet is moved sideways by the width of one line, it moves up to the position of the line which had been occupied by the line immediately above it. If you do not believe this, try the experiment for yourself. Take two sheets of glass—say, those sold for use in cold-frames—and paint diagonal lines on each, as shown in the diagram.

Now there are two things to note. The first is that these fringes are spaced farther apart than are the lines: thus they are easier to detect.

Secondly, there is an averaging effect, so that any inaccuracies in individual lines are eliminated.

All that remains is to put a piece of metal with a slit in it in front of this system and shine a light through the whole thing. It will then be seen that as one sheet of glass is moved sideways a series of flashes move across the slot as the diamonds pass it. These flashes can be counted by an electric eye, coupled up to counting equipment.

This, in fact, is what is done: two diffraction gratings are used, one stationary and one attached to the cutting edge. As the moving one slides over the fixed one, flashes of light pass through it which are electrically counted. In the machine-tool arrangements can be made to stop the movement when a predetermined number of flashes has been detected.

At this stage a big firm of electronic engineers saw the possibilities of this and devised a counter which would work equally well for both directions of movement. Before long the device was applied to an actual machine-tool.

To show this we brought to the screen, by means of film, Mr Harry Gregory, General Manager of a large aircraft company in Stockport, near Manchester. This company designed and built the machine-tool to accept this control system. On film we were able to see the machine milling—that is, cutting out of metal a large and complicated shape for use in aircraft. The control-cabinet looks very much like a tape-recorder, and basically that is what it is. Once the control-tapes have been made, the machine can spend the whole of its time cutting, no time is wasted on resetting and adjusting it. As Gregory said, 'This does, in fact, mean that we can produce parts more accurately, quicker and cheaper. It is my belief that far more of these machines will come into use in industry and this has been made possible by the diffraction grating system, by the National Physical Laboratory and the backing in our case that we received from the Ministry of Supply.'

Sayce showed me yet one more application of this line of research. Here the object was to make a very accurate precision lathe even more accurate by letting it measure its own inaccuracies and correct them. This is a line of development which might have revolutionary effects on the engineering industry.

In his lab he has a very accurate precision lathe, geared to cut a very fine screw-thread of a thousand turns per inch. How accurate it

was and how easily disturbed could be shown by simply pressing one's finger on the end of the lathe. For the advance of the lathe saddle was being recorded by means of a pair of gratings, one of them attached to the bed of the lathe and the other fixed to the saddle. These gratings were ruled with a thousand divisions to the inch, and an electrical signal was taken off them by a light-sensitive cell, and fed into a pen recorder, drawing a line on a roll of paper. If the lathe were behaving perfectly the pen would draw a straight line down the middle of the chart.

In fact, the line which the lathe was drawing when I saw it was a rather wavy one. There were rapid fluctuations and the line as a whole drifted slowly from side to side on a longer-term basis. This made it look as if the lathe was behaving very badly, but of course the errors are much magnified. Every sixteenth of an inch which the pen moves corresponds to one millionth of an inch of misplacement of the lathe saddle. Merely pressing one's finger gently on the lathe saddle, causing a quite imperceptible sideways deflection, caused the pen to shoot sideways across the chart.

Having got the lathe to record its errors, the next step was to record the error automatically, by feeding the electric signal's report of error into a servo-system which would move the tool into the ideal position. In other words, the report which the lathe was issuing on its errors was used to cancel out those errors. This could be shown very clearly by switching on the control system; immediately the pen moved back to the middle of the chart, and from then on the line was straight down the middle indefinitely. The lathe had been made the slave of the grating. This, of course, is a principle which could be applied to any machine-tool where high accuracy is required.

As Sayce explained, this was pure research, but one could foresee many practical uses. For instance, with this lathe one could cut a very accurate screw-thread and then use this screw-thread, in turn, to drive the lathe, producing an even more accurate screw-thread, and so on. The heart of any machine-tool is the screw-thread, the so-called 'lead screw'. If you have perfect lead screws in machine-tools you can produce much more accurate parts. It could well be that in a mass-production line equipped with perfect threads one could start mass-producing with the kind of accuracy which is today only achieved by a most skilled craftsman.

Before this can happen, of course, there is a good deal of develop-

ment to be done. For instance, very accurate diffraction gratings are being made in which the divisions are arranged radially, i.e. like the spokes of a wheel, instead of in the form of parallel lines, so that movements through an angle can be measured and regulated just as well as linear movements. Thus engineers need no longer rely on screw-threads and division-plates for accurate measurement but can make use of optical gratings and attain a much higher standard of measurement. These devices may, therefore, well set a new standard of engineering precision. In particular, the construction of radial gratings should make the cutting of gears better. It is hardly too much to say that they are bringing about a new industrial revolution, in the sense that the machine-made object need no longer be less accurate than the hand-made.

o'clock. By arranging the speeds of the dials it was possible for twelve o'clock to come up sometimes frequently and sometimes only at considerable intervals and also for twelve o'clock to come up on a number of dials at the same time. By studying when he pressed the lever one could see whether he overlooked certain twelve o'clocks and also what he did when they were concentrated closer together than he could cope with. But this kind of device could not tell you whether he favoured one particular dial rather than another—whether perhaps he was more likely to miss twelve o'clock when it came up on the edge of the array than in the middle.

It was clear that what was needed for such investigations was a device which would show exactly how the operator was using his eyes. Mackworth started from the idea that if a very small spot of light was shone on the eyeball it would be reflected and could be picked up by a television camera. When the eyeball moved this spot would also move. The difficulty in this idea was that the operator must not move his whole head as this would alter the relationship of his eyeball to the beam of light striking on it, and indeed might easily move his whole eye out of the line of fire. In the initial experiments, therefore, the operator was required to close his teeth firmly on a mouthpiece, shaped rather like a dental impression, and also to lean his forehead against a curved band in an attempt to hold his head as nearly motionless as possible.

Mackworth then had a device which, though not very reliable in the sense that inadvertent head movements could upset it, would record the movements of a man's eye as he read a page of figures or looked at a moving demonstration. He next improved upon this idea by putting a second television camera to pick up a picture of what the subject was looking at. Then by feeding the output of both this and the first television camera which was picking up the light reflected from the eye into a single monitor—that is, a sort of television set—he could see the spot of light representing the position of the man's eye superimposed on a picture of what he was looking at.

Mackworth showed me a film made with this device in which a man tried to find a particular figure in a whole table of figures. It was intriguing to see how his eye passed rapidly over the correct figure without noticing it and then, reaching the end of the table without apparently having found it, began to search madly and erratically backwards and forwards in an attempt to locate it.

With it, Mackworth was able to study basic eye movements, divorced from any particular task. Rather interestingly, the device showed that while a man can follow an object moving in a circle with his eye fairly smoothly, provided the speed is not too great, yet if he is asked to move his eye in a circle without any object on which to focus it, he moves it in a series of jerks. It showed also that reading takes place in a series of jerks and that the size of these movements differs from one person to another. These movements are being studied further.

Meanwhile, Brian Shackel, who had previously also been a member of the Applied Psychology Research Unit, set about trying to find a method of achieving the same result which would not involve holding the head completely still. He started from the fact that the eyeball is a miniature battery producing very small voltages. The currents produced are about ten million times weaker than ordinary electric lighting current. These voltages can be picked up at a number of points round the eyeball and by very considerable amplification can be made large enough either to operate pen-recorders or even to produce a spot of light on the television screen.

Wires are therefore attached to the subject's skin at three points near the eye—above, below and to one side. The wires are attached to the skin by little drops of collodion, a substance which soon dries off, but before this is done the outer layer of dead skin is removed with a dental drill. The process is quite painless, as only dead skin is removed, and this is perhaps the only time when people suffer the attentions of a dental drill without complaining.

With some people, loud noises cause a sudden increase in the skin's electric currents and thus upset the accuracy of the registration: the use of this drilling technique obviates this.

Shackel's method also has some minor disadvantages: for example, the level of these currents may change slowly with time so that at intervals it is necessary to check that the recording spot really is on zero when the person being examined is actually looking at the centre of his visual field. For his present experiments Shackel usually brings his results out on pen-recorders: two pens are used, one of which records the left and right movements and the other of which records the up-and-down movements of the eye. Thus, when the eye is moved diagonally both pens will change position. The advantage of using pen-recorders is that the long rolls of paper on which the pens record can be filed for reference and analysed at leisure.

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Shackel has been examining a number of naval ratings with this apparatus and, to his surprise, discovered that there are occasional men who have great difficulty in focusing their eyes on a particular point. In his experiments he customarily asks men to fix their eye on a spot which is then moved step-by-step to the left and then step-by-step to the right. One can see from the pen-traces that most men have little trouble in directing their eyes at the correct position, but one or two err first on one side, then on the other and seem unable to hold the spot directly in view. The reason why a few people have this deficiency is still not known, nor do we know anything about how numerous such people may be in the population as a whole. In Shackel's studies two men out of 120 were found to be affected.

Such a failure to 'fixate'—or hold the gaze steady—might well affect a man's performance at tasks such as rifle-shooting. Hence these eye-movement recorders may prove to be useful aids in helping people to select the right man for the right job.

You may have heard that the eyes are never still. This statement is, in fact, based on work done not by Shackel or Mackworth but by Professor Ditchburn and his colleagues at Reading University. The movements which Ditchburn studies are much smaller than those with which Mackworth and Shackel are concerned. They seem to be due to the fact that the eye attempts to save the retina from becoming tired. If the eye remained completely stationary while one gazed at a particular image, since each part of the image is brought to a focus at the back of the eye, the light falling on the various sensitive cells—the rods and cones—would gradually exhaust their power to respond to it. This would be particularly likely to happen in cases where the object observed was very bright. The eye, by moving continually, shifts the image about on the retina and prevents the nerve endings in the retina from becoming fatigued and causing the power of vision to be temporarily lost. These oscillations of the eye cover only a fraction of a degree and are almost invisible. Thus they contrast with the relatively large movements, which may be as much as thirty degrees, which are studied by the eye-movement recorders I am describing.

Devices of this kind have many future applications. For example, we know very little about how people who inspect the output of industrial products do their work: what points do they look at and are they more likely to miss defects in one part of an object than in another. A very good instance for study would be the inspection of

signal from it and fed it not to his monitor, but right through to the BBC television transmitters, so that the picture, complete with the subject's 'point-of view', appeared on the viewer's television receiver. As the subject moved his head, everyone could see the picture change, and, as the subject moved his eyes, they could see the 'point-of-view' move correspondingly.

Another application of these methods is in the field of radar. Radar operators have to watch their scopes for long hours during which nothing whatever may come up, and boredom makes it very easy for them to overlook blips when they occur. Experiment has shown that attention improves when there is something to attend to, and after one blip has come up people watch with more attention for the appearance of the next. On the other hand, when there is a great deal going on on the scope they may miss part of the display.

The Admiralty, therefore, thought it worth their while to fix up eye-movement recording apparatus of this type in a mobile laboratory which could be taken to different establishments in turn. In it a simulated radar display was mounted so that the way in which the operators searched the end of the scope could be studied in detail. It has already been found that they are more likely to overlook signals appearing at the extreme edge of the screen, and representing aircraft perhaps thirty miles away, than they are signals in the centre which might be within a radius of ten miles. (These figures, of course, are those of the particular screen installed and might be very different in some other set of circumstances.)

Yet another interesting application to which Shackel's version can be put is to record the eye movements of someone who is asleep. It has been shown that people move their eyes a great deal while they are dreaming. This was discovered by waking people up whenever such movements were being recorded and asking them if they were dreaming. By comparing what they say with what they say when they are woken up at a time when their eyes are not moving, it has been possible to establish the fact that eye movements usually go with dreams. As a result, psychologists are now using the presence of eye movements as a way of discovering how much of the night different people dream. They have shown that this varies a good deal from one person to another, and at different times with the same person.

In science it is often the case that research can only proceed when

a suitable tool has been devised with which to carry it out. In this case the idea of studying eye movements was originally proposed more than a hundred years ago but it is only now, with the advantage of electronic techniques, that it has been brought to the state of practical application.

The programmes described in the last four chapters have all concerned work done in laboratories financed by the State. The wind-tunnels belong to the Royal Aircraft Establishment, the Hydraulic Research Station to the Ministry of Supply, the National Physical Laboratory comes under the Department of Scientific and Industrial Research, while Mackworth's work (and, at first, Shackel's) was financed by the Medical Research Council. All this work was directed at the solution of immediate practical problems.

I wanted, however, also to show pure research, such as is done in universities, where the spirit of curiosity and the desire to understand is the main driving force. In such work though practical benefits almost always are reaped in the end, the desire for them has little or no influence on the choice of a subject for study.

I was also anxious to see if it was not possible to show on the screen something of the newest advances in the biological and particularly the biochemical field. How we achieved both these aims makes the subject of the next two chapters.

6

The Thread of Life

Report on a Biologicol Breakthrough.

About two-fifteen one cold day in January 1958 I found myself with the producer, Aubrey Singer, sitting in the gleaming laboratory of Professor Harriet Ephrussi-Taylor in a building at Gif-sur-Yvette, about twenty miles south of Paris. We were eating slices of cold ham from circular filter-papers, and in the next lab an American research worker was boiling up some coffee for us in a beaker, which normally contained biological fluids, over a Bunsen burner.

The reason for this was that the eight o'clock plane had been grounded by fog until nearly midday, so that although we drove straight from the airport to Gif, we arrived late for our appointment and not having eaten since an early breakfast, Professor Ephrussi-Taylor took pity on our famished state.

We had come to ask her to take part in the most ambitious programme the *Eye on Research* series had yet attempted—ambitious both in the sense that it brought together material from a great number of places and required very careful writing and organization and also in the sense that it attempted to explain something difficult. We made this special effort because what we had to report was of the greatest possible importance. Many biologists would say that it is more important to mankind than the atom bomb. It is certainly the biggest breakthrough on the biological front this century.

It is the discovery of the structure of the mysterious molecule which lies within the centre of every cell in the body of every animal, plant and living thing and which determines its heredity. In the case of human beings, it determines whether you will have blue eyes or brown, be tall or short and, indeed, all your physical characteristics. It determines whether you are male or female, coloured or white.

This mysterious substance is called nucleic acid. To be exact there are two nucleic acids, the principal one, with which we are here concerned, being known as deoxyribose nucleic acid, or DNA for short. (The other is ribose nucleic acid, or RNA.)

To tell the story of DNA and how its structure was established and why this was important we sent camera units to Paris, Cambridge, London, and also brought scientists to the studio, as well as showing specially-made films from the Sloan-Kettering Institute for Cancer Research in New York. Professor C. H. Waddington, of the Department of Genetics in Edinburgh, linked the programme together.

The existence of DNA has been known for many years but its function was until recently obscure. We went to Paris to ask Dr Ephrussi-Taylor to take part because she was originally concerned with an experiment which revealed the crucial character of DNA very clearly.

Dr Ephrussi-Taylor works with bacteria. The reason for choosing bacteria rather than some other organism is simply that it was in the bacterial field that the effect of DNA was first observed: this in turn was because the phenomena in question may turn up only once in a million times. Consequently if one uses colonies of about fifty million bacteria there is a reasonable chance that some of them will display the change which is being studied. The actual bacteria she uses are those which cause pneumonia. When a small drop of liquid containing a few of them is placed on the nutrient medium called agar jelly, which contains all the food which bacteria need, they multiply freely. Within twenty-four hours a blob can be seen with the naked eye. This is called a bacterial colony.

This technique of 'plating out' on agar jelly provides a convenient way of spotting whether you have got any bacteria in your drop to begin with and constitutes a standard research method. Bacteria grow to maturity and produce a daughter generation about every twenty minutes when conditions are favourable so that one can study a good number of generations in a reasonable time. But the hereditary processes which the bacteria exemplify are similar in plants and animals of almost every kind. The experiment Dr Ephrussi-Taylor was about to show us was one in which a hereditary characteristic of one kind of bacterium had been given to another strain of bacteria by taking the DNA out of one and putting it into the other. 'You can

see,' she said, putting one of her preparations of bacteria under the microscope, 'that these colonies of pneumococci—that is, pneumonia bacteria—have a smooth outline. Under the microscope they look like drops of oil—that is because each one has a smooth, slimy coat. And if we take off one or two of the bacteria and let them grow into a new colony, it will be smooth too, and so on for generations. But every now and then we get a colony which has a rough outline. This means that the individual bacteria lack the outer coat or skin which such bacteria normally have.

'Now this is where DNA comes in. If I mash up one of these *smooth* colonies and extract the DNA with various chemicals and then add it (using a sterilized pipette so no other bacteria get in by mistake) to a broth containing *rough* cells—add smooth to rough—we shall find in about an hour that about half the cells in the broth are beginning to produce *smooth* cells—that is, we have given the hereditary factor for having a skin or capsule to cells which had no skin, and have forced them to produce coated cells. We have changed their hereditary pattern. To get this result, I use not neat DNA, but DNA diluted with a million times as much water. After a few minutes, when the DNA has had time to penetrate some of the bacteria I smear a few drops of the moisture on a clean plate of agar jelly. As a check, a few drops of the solution of bacteria to which no DNA has been added are smeared on another agar plate.

'And we can do this for other hereditary factors. As you know, most bacteria are killed by penicillin, but sometimes we come across a strain which is resistant to it. We can take DNA from these resistant bacteria, treat the normal susceptible ones with it, and, lo and behold! they produce resistant offspring.'

There is another even more extraordinary demonstration which shows the unique properties of DNA. It concerns a kind of virus called bacteriophage ('bacteria-eater') because it preys on bacteria. The phage attaches itself to a certain large bacterium, known as Escherichia coli. Now phage consists of a bit of DNA with a sort of envelope of protein round it. (Protein is a name for a large group of complex substances. Muscle is built of proteins—which is why dieticians speak of meat as protein.)

Under the electron microscope the phage can occasionally be caught in the act of squirting its DNA into the bacterium. About twelve minutes later you find scores of bits of DNA

constantly divide in two as the animal grows. In fact, we all start, human and animal alike, as a single cell, an egg.

Now whenever a cell divides, certain rods appear in the nucleus and divide along their length, so that the daughter cells each receive a similar endowment. We call these rods *chromosomes*, and biologists have established beyond doubt that they carry the hereditary instructions on from cell to cell. They carry it on into the egg, when it is formed by the female parent, or into the seed in the case of a plant, and so the pattern passes to the next generation, with allowance for the fact that the father also contributes his heredity, and the two sets of hereditary instructions became reshuffled.

Each chromosome makes an exact copy of itself, and when the cell divides, these pairs are cleanly separated, so that each new cell gets an exactly equal share. That, of course, is just what would have to happen if the chromosomes are to carry the hereditary potentialities.

Furthermore, study of these chromosomes has established the fact that the power to regulate a particular feature of growth is located at a particular point on the chromosome. These points are known as *genes*. (Some features, such as stature, are the product of several genes acting on different features of the growth process.)

This has been discovered by very ingenious observations. When the egg or the sperm are being formed—these are known as germ-cells—they are produced by a division of a slightly different kind, in which the germ-cell receives only half the total number of chromosomes from the parent cell. Consequently, when the sperm and egg fuse in order to set off the development of a new living creature, each brings a half-complement of chromosomes, so that the fertilized cell has the normal number again, and in this way the offspring derives hereditary factors from both parents.

Now, in the ordinary way all the hereditary factors of a particular chromosome will be inherited together. If a particular chromosome does not get into the egg, because it is not one of the 50 per cent which is selected in any given case, none of the factors it controls will be inherited. But sometimes breaks occur in the chromosomes, and the chromosomes subsequently join up again incorrectly, half one chromosome joining on to a fragment of another. In this case, of course, the packet of inherited characteristics changes, and by studying such breaks under the microscope in simple organisms

like moulds, and then waiting to see what difference they make in the behaviour of the organism which results, it is possible to find out precisely where on the chromosome each characteristic is located.

For example, many bacteria have the power to synthesize some of the amino-acids, which are the foodstuffs off which bacteria live. Thus one strain may be able to dispense with the amino-acid valine in its diet, although it requires tyrosine, because it can make the valine for itself. If bacteria which has this power mates with one which has not, then one can easily find out whether the ability has been transmitted to the offspring or not, by seeing whether they can survive on agar jelly which contains no valine.

It will be realized that the farther apart two characters are in a chromosome the more likely it is that a breakage and rejoining will happen between them, and so by studying how *often* two factors are inherited together, or how often they are separated from one another, one can get a mathematical measure of how far apart relatively they lie. In this way one can make maps of the chromosomes showing where the various factors are.

These experiments show, to begin with, that the hereditary factors are arranged in a straight row or line and this suggests that the DNA, which must come into the story somewhere, must also have a linear character. It is in these chromosomes that the DNA is located, the rest consisting of protein (nucleoprotein). This has long been known but until recently it was supposed that it was the protein which convey the hereditary information.

While we are on the subject of making chromosome maps, it is worth adding that with most animals one cannot handle enough individuals to detect the breaks which are rarest, so the smallest interval between factors which it is practical to spot is one which would be large from the point of view of a chemist. Working with phage, however, Dr Benzer, in America, has managed to detect gene spacings which appear to be only a few chemical groupings apart, and in Glasgow Dr Roper has achieved similar results with a mould called *Aspergillus*.

That was about as far as the biologists and geneticists had carried the story. Heredity seemed to be transmitted by something ranged in a long line and constructed of building blocks, each one of which in some way controlled a particular feature of heredity. At this point

the chemists made their contribution. Sir Alexander Todd received the Nobel Prize for establishing the chemical structure of the immensely complicated molecule which is DNA. He and one of his colleagues, Dr Brown, described some of the methods which the chemists used for finding the structure of DNA. The first step was to break it up with acid, and the problem was to separate the various pieces and identify them. This was done by a method, now widely used in science in a number of different forms, called chromatography. In this particular version—paper chromatography—the mixture of pieces from DNA produced by the acid is put, as a spot, on a piece of filter-paper and a special solvent is allowed to flow over it in a tank. This washes the various substances down the paper, but at different rates, so that they become separated into discrete spots. After drying the paper the spots can be seen, if looked at in ultraviolet light, or by spraying the paper with special chemicals which bring the spots up in different colours. The substances separated in this way can be identified and the main work of the chemist then begins. It is to find out how these pieces are joined together in the original DNA.

There are, in fact, six important break-down pieces. Two of them are now known to form the backbone of the molecule. They are phosphate and a rare sugar called deoxyribose, only found in DNA, which is rather different from the sugar we are all familiar with.

The DNA chain, then, is made up of large numbers of sugar molecules alternating with phosphate and joined in a particular way. The other four components, the bases, are attached to each sugar as, one might say, clothes hang from a washing-line, and the order in which they are attached varies. There are many thousands of articles of clothing on the line but only four types of garment. Thus, one has a molecule which, while constructed out of fundamentally the same material, can vary in the sense that the order of garments on the line can form a great many varied sequences: presumably these differences of sequence correspond to the differences of heredity. This, of course, is still pure speculation but it is a speculation, as we shall see, not without a solid basis of circumstantial support. Opposite is the pattern. The main chain, consisting of a kind of sugar, linked by groups with an atom of phosphorus at the centre (see Fig. 2).

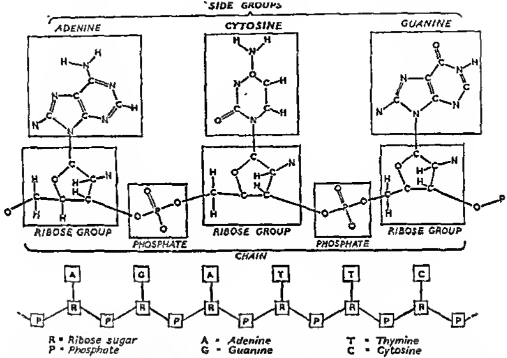

FIG. 2.—Section of DNA molecule. This pattern is repeated through several thousand units, the order of the side groups varying. (The fourth side group, Thymine, is not seen in the top diagram.) The lower diagram shows it schematised.

But from this chemical analysis two other things emerged. Firstly, that the proportion of DNA components varies according to the animal from which the DNA is derived. Secondly, that the four components are always present in such a way that the quantity of A always equals the quantity of B, while the quantity of C equals that of D. This suggests that they go in pairs. The four substances I have here called A, B, C and D are, in fact, the chemical groups known as adenine, cytosine, guanine and thymine. One can also think of this chain as comprised of units consisting of a side-group, a sugar and a group with a phosphorus in it—and this combination is called a *nucleotide*. The chain then can be thought of as consisting of a long succession of four possible nucleotides.

While the chemists could establish this much, it was not the whole story, for the atoms do not lie flat in a single plane as they are shown on the paper, but orient themselves in three dimensions in space. This is because the bonds which join adjacent atoms can only take up certain positions.

To answer the question how the chain is arranged in space it was necessary to call on the help of physicists. Here Dr Maurice Wilkins of the Medical Research Council, Biophysics Unit, who works in Professor Randall's laboratory at King's College, London, takes over the story. He is an X-ray diffractionist. In X-ray diffraction, X-rays are bounced off the molecule under study in order to discover in what directions they are reflected. X-rays are used because the X-ray travels in a series of waves which are about equal to the distance between the atoms in a molecule and so the atoms interfere with the X-rays in a special kind of way. Sometimes the rays of the X-ray can squeeze in between the atoms and, when they come out the other side, their directions are changed. If a photographic plate is exposed to the rays thus deflected a rather regular pattern of spots appears on it. Measurements of the spacing and intensity of the spots makes it possible to work out something about how the atoms must be arranged within the molecule.

Working with DNA specimens obtained from Professor Ephrussi-Taylor in Paris or from Dr Hamilton at the Sloan-Kettering Institute in New York, Wilkins obtained many pictures and proceeded to analyse them. This involved complex mathematics and the use of an electronic computer.

What came out of all this was that the molecule must have a sort

of corkscrew arrangement, for the pattern clearly repeated in some regular way.

'What we want in this kind of work,' said Wilkins, 'is a sort of inspired guess so that we can work backwards with the X-rays from the guess and see if it could be true.' Wilkins had been discussing the problem with his friends, Dr Watson, an American biologist, and Dr Crick in Cambridge, with whom Watson was at that time working. They had a very brilliant idea, which was just what he wanted. It is best made clear by a diagram.

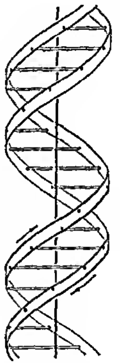

FIG. 3.—The double helix of DNA. This diagram conveys the underlying structure of DNA. The two ribbons represent the two intertwined chains of alternate phosphate groups and ribose sugar groups. The horizontal rods stand for the pairs of basic groups which hold the chains together. The black vertical line has been drawn in to make clear that the two chains twine round and round, in the manner of a "spiral" staircase.

What they suggested was, in fact, that there was not one corkscrew, or helix to use the correct word, but two of them intertwined—a sort of double corkscrew—and they further suggested that the two chains were joined together by the pairs of chemical groups which the chemists had discovered. This accounted effectively for the fact

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that the quantities of the two pairs of basic groups, A, B, C, D, being equal. This model was also attractive to the biologists because what they wanted was something which could split down the middle and give identical parts to each of two daughter cells and, clearly, a double helix could be taken apart into its two components, at least in principle, for this purpose.

With this very attractive idea, Wilkins and his co-workers went back to his X-rays and did some further calculations, with the aid of an electronic computer. He ended up with a fairly specific model of the probable structure of DNA. In fact, one of the models made to exhibit it was shown in the British pavilion at the Brussels World Fair, and in it was set out the exact position of all the atoms, the oxygen, the hydrogen, nitrogen, and so on, except that only about three feet of the helix were made (see Plate 6). Really, however, if it were to represent the real thing at this scale it would have to be about a mile long.

This, of course, was exciting for the geneticists like Waddington who felt that this could meet their needs, and experiments were soon performed to try and check whether the DNA did split down the middle as they expected. By labelling molecules with radioactive atoms so that one could trace what happened to them, it was found in a particular case that when the DNA from one parent was labelled and not from the other, half the DNA from each parent fetched up in each daughter cell. The fact that the DNA really does divide in two was recently even more conclusively shown by a very ingenious and delicate experiment devised by Drs Stahl and Meselson at the California Institute of Technology. They induced bacteria to make DNA from materials containing only 'heavy' nitrogen. These molecules therefore weighed a little more than normal. After any given bacterium has subdivided twice, one would therefore expect that two of them would contain DNA in which one half of the DNA helix would be heavier than normal, because it would contain half the original heavy DNA molecule. Stahl and Meselson then had to devise a method of weighing so delicate that they could detect this difference if it existed. They found it did. Had the DNA simply been broken down into its basic units and re-used, the four daughter bacteria would, of course, have all weighed the same.

Another thing which tended to support the model was the fact that the distance between the side groups, as worked out by Wilkins,

was just about the same as the distance between neighbouring genes as plotted by Dr Roper and Dr Benzer. It may seem incredible to suggest that the changing of the order of four basic groups could control the whole elaborate scale of characteristics which are inherited by complex creatures such as ourselves. Nevertheless, there is much evidence that very small chemical changes can have very big practical results. For example, there are a number of diseases which are due to small changes in the constitution of haemoglobin, the substance in the blood which carries the oxygen from the lungs to the muscles. One of these is the well-known disease sickle-cell anaemia, which is rather common in Africa; there are variants in other parts of the East.

Dr Ingram, at Cambridge, who appeared in the programme to make the point, has shown that the difference between the healthy and the sickle-cell haemoglobin is constituted by a single chemical group in this enormously complex molecule. It is not unreasonable therefore, if we conceive that the DNA controls the structure of proteins, to assume that a single change in the DNA could produce a corresponding change in the protein, and this particular change is a matter of life or death.

The present guess is that the DNA acts as a kind of template. The processes of growth depend upon substances known as enzymes which make certain chemical reactions possible, and there is some evidence that these enzymes are lined up in a particular sequence so as to bring about a series of chemical reactions in a particular order. The question has always been, what lines the enzymes up, if this is so? Now it is not inconceivable at all that the enzymes could fit into the complicated interstices of the DNA molecule and be held in a particular order. The exact shape of these interstices would depend upon the way in which adjacent side groups happened to come together on the spiral, depending upon what particular groups were present at any point. We can imagine the outside of the molecule as having numerous different-shaped slots so that into a slot of a particular shape, a particular enzyme might conveniently fit.

To sum up then, the biologists, the chemists, and the X-ray diffractionists have produced an account of the structure of DNA which meets all the known requirements.

Meanwhile, research continues feverishly. In New York Kornberg and his colleagues have been trying to synthesize DNA by mixing

together the various components. They have found that a synthesis will take place if a certain amount of genuine DNA is put in first to start it going, by acting as a template. Enzymes taken from living organisms also had to be added.

However, since then the theory has been put forward that in the cells of the body DNA is constantly being formed and broken up and this gave rise to the idea that one might be able to arrest it when it formed by embedding it in something which would discourage it from breaking up again.

Bendich and Rosenkranz, of the Sloan-Kettering, have recently synthesized DNA for the first time outside a living cell, by shaking up a solution of nucleotides with a cellulose material (Ecteola) which has a strong affinity for DNA. From the cellulose they were than able to wash out a substance which has all the chemical properties of DNA and which, furthermore, is taken up by living bacteria, just as normal DNA is. (This is regarded by many scientists as so surprising that they doubt the validity of the experiment.)

In the next chapter I shall tell how DNA also throws light on the way in which the virus—the incredibly small disease-causing particle —does its work.

But apart from this aspect of the subject, and it is an exciting one, the opening up of the question of heredity by the establishment of the structure of DNA, is sufficiently exciting in itself.

For instance, it looks like throwing fresh light on the problem of the causation of cancer. As Dr Hamilton explained in a special film made in New York, we know that powerful radiation from X-rays or radium can cause cancer and we know that radiation disorganizes DNA. We begin to see, therefore, that cancer or, at any rate, some kinds of cancer, may be caused by some fault developing in the structure of the DNA molecule. Possibly certain substances derived from tars, which are known to cause cancer, act in the same way; or, if they do not damage the DNA itself, they may block up the mechanisms by which it controls the cell.

Another possibility is that viruses, which also contain DNA, may contribute their brand of DNA to the cell and that this may take over the conduct of the growth, rather as it did in the experiment which Professor Ephrussi-Taylor showed in the case of bacteriophage.

One main line of cancer research, therefore, is to collect samples

of DNA from the blood of human patients and to bottle and post it to laboratories in many parts of Europe and America for study. The immediate object is to find if there is some substance which will block the growth of the cancerous cell without harming the healthy cell. Progress has been rather mixed so far—a few substances, such as azaserine, have been found, which cause mouse cancers (mice are the usual experimental animals) to improve for a time. But after a while the cancer seems to adapt itself to the new situation and gets worse again. These experiments have, until recently, been done pretty much in the dark as to how the substance chosen for test was working. As the structure of DNA becomes understood, it may be possible to find out why these partially-successful substances *are* partially successful, and from this to devise others which will do better.

It is known that these substances work on the principle of throwing a spanner into the works—that is, they resemble some substance the cell normally uses, but are sufficiently different that, when they are taken up by the cell, the manufacture of DNA is stopped. For example, one of the sub-assembly lines so to speak, of DNA, requires the vitamin known as folic acid, which plays a part in the chemical reactions involved. The cell will take up chemicals which resemble folic acid, but they are not able to participate in the reactions by which DNA is made. In the same way azaserine competes with the natural substance, glutamine, and prevents its work. There is another substance known as 6-mercaptopurine which imitates the natural building block adenine, and inhibits growth by slipping into the place of this natural purine.

The possibility of intervening in disease, however, is only the beginning of what this work implies. The possibility is very real that the scientists who are working on DNA and its associated substances in a score of different laboratories in France, Germany, Denmark, Britain, America and elsewhere, may find out how to change the structure of a particular DNA. They may be able to knock out a particular segment and substitute another which they may have derived from some different creature or even from an animal of a different species. If they then inject this reconstituted DNA into the organism from which it came, what will happen to it? What will the organism become? The guess is that it will acquire the characteristics proper to that particular group of DNA segments with which it has been treated.

Thus, in this case it will become possible to tinker with heredity.

But if the American workers, who are trying to synthesize DNA, can produce completely new DNA's which have no relation to any existing animal, what would this DNA do when injected into a living creature?

Further than this, in London another worker is providing DNA with a broth of the raw materials from which cells are constructed, to see if it can build protein, the basic cell material, in a test tube. This, if he succeeds, will be remarkably near the creation of life. Furthermore, if he succeeds with natural DNA, perhaps he or some other worker will later succeed with a DNA which has been synthesized. Thus the possibility opens up not merely of creating some existing form of life but of creating some brand-new form of life. Such forms would certainly be, in the first instance, quite primitive ones, probably viruses—and it may be that even now in the world there is some completely new disease which science has created.

Such work opens up extraordinary possibilities, of far-reaching practical importance to everyone. For instance, if chemists can alter the structure of the DNA chain, they may be able to build disease-resistance into the DNA—I already described how this happens with bacteria. To do it with large animals may prove more difficult. Biochemists do not know how they can put the reconstructed DNA into the egg, but there is evidence that this may not be very difficult. And once it is in, it will continue to affect every succeeding generation.

Further, it seems that RNA—DNA's first cousin—is the messenger which carries the hereditary patterns into the body of the cell. If we can understand and alter the structure of RNA also, we are getting near the possibility of altering the hereditary pattern not merely of the next generation, but our own. We might then be able to change people's heredity after they had been born.

We, as members of the public, must do some thinking about the social implications of DNA. If it is going to be possible to play about with the hereditary pattern, a real eugenics becomes possible, with far-reaching effects on plant and animal breeding to begin with. We shall be able to construct new strains with desirable features—cold-resistance, for instance—just as we can now construct new plastic materials. If this is applied to humans by any government, can they produce a race of supermen? Not only cleverer and more

powerful, but resistant to disease, radiation or the cold or outer space? What would this mean for the racial problem, if one could remove or alter skin-colour?

I do not think it is very risky to forecast that in ten years' time we shall be discussing the moral implications of DNA with the same, or even more concern, than we now discuss the moral implications of the atomic bomb.

7

Smaller than Life?

How scientists are exploring the structure of disease-causing viruses too small to see even with a microscope.

When Aubrey Singer asked me for an idea for a large-scale programme with which to open the new *Eye on Research* series in the autumn of 1958, I immediately suggested that we should do a programme on viruses. A great mass of work is being done all over the world on these incredibly minute disease-causing particles which are responsible for such human diseases as polio, influenza, mumps and the painful skin-infection, shingles. They also cause animal diseases, such as foot-and-mouth, which costs the country millions of pounds a year, and many plant diseases such as those which attack tobacco plants, the tomato disease (bushy stunt), and the turnip disease (turnip yellow mosaic) and sugar beet yellows virus. This last alone costs the country several million pounds a year. Viruses also attack bacteria, butterflies and caterpillars, and even the common clothes moth. Strange to say, however, they do not attack the non-flowering plants, such as ferns.

Incidentally, some plant viruses cause rather beautiful variations in the colouring of the petals of flowers, such as tulips—variations which people often imagine are due to some kind of crossing.

Just after I made this suggestion, there was announced the discovery by Dr Alick Isaacs and Dr Lindemann at the National Institute of Medical Research at Mill Hill, of a material which will interfere with virus growth and thus holds out some promise of curing these virus diseases. At present, virus diseases can only be cured, if at all, by helping the body's own defence mechanisms. But the pace of research is rapid, and at last scientists begin to see what they are dealing with.

Substances, like the antibiotics, which are effective against bacteria, are, with one exception, quite useless against the far smaller viruses. (The exception is aureomycin which is effective against typhus—and it is important since it provides grounds for hoping that there may be other antibiotics against viruses).

Up to now, the bulk of the research into virus-structure has been done with the virus which causes a mosaic or markings on the leaves of tobacco plants, known as tobacco mosaic virus, or, among scientists, as TMV. It also attacks other plants, such as cucumbers, but was first spotted in tobacco plants and thus received its name. It is perhaps interesting to mention how it comes about that scientists pick a particular organism, or in this case, virus, for intensive study. There were several reasons for the selection of TMV. It had just been isolated and purified by Professor Robley-Williams in America. It was available in the relatively large quantities required for research, since it could easily be grown on tobacco plants in greenhouses; and it was available to workers in many different parts of the world. If each had chosen a different virus to work on, their results could not have been dovetailed together. It is also a very stable virus—some viruses seem to change their habits and presumably their structure rather unpredictably. Finally, since it affects plants like tobacco and cucumber, it is of some commercial importance.

Viruses are incredibly small—so small that they can pass through the finest filters, even through fine-pored ceramic materials, through which liquids pass, like water passes through the walls of a flower-pot. For many years they were known as 'filter-passing viruses'. Indeed, the only reason for supposing they existed was that if one filtered the blood of a diseased animal and then injected the filtrate into a healthy animal, it also would fall prey to the disease. Clearly something was passing through the filter which had the power of multiplying itself within the host animal, much as bacteria do, until present in large enough numbers to cause disease.

The power of self-reproduction is usually regarded as peculiar to living creatures, yet this liquid filtrate could be crystallized, i.e. dried out to form crystals, like many other chemicals: it must therefore have a very regular shape

What is this mysterious thing, which shares the properties of living matter and of dead, which no one can see?

It seemed to me that to make this programme effective it was vital to establish in people's minds how really incredibly small the virus is. It is actually smaller than a wavelength of light and thus is quite invisible in the most powerful of ordinary microscopes. (It can, however, be seen by means of a complex instrument called the electron-microscope, which does not use light waves (see Fig. 4.)

Viruses vary in size, but, taking an average, we may say that the virus is about 800 times smaller than a human blood-cell. To bring out just how small the virus is, I had the idea of asking Raymond Baxter, the sports commentator, whom we had asked to come in and introduce and help link this series of programmes, together, to prick his finger. Actually, when it came to the point, he was told by the experts that he should cut his finger with a piece of glass, which is the professionally correct way of obtaining a drop of blood. We then put a tiny smear of this blood on a microscope slide and showed it magnified 800 times, so that the individual blood-cells could be seen. Thus the virus is as much smaller than the blood-cells as the blood-cells are themselves smaller than the original drop of blood.

The electron-miscroscope which makes it possible to see the virus consists in essence of a vertical tube some four feet long, at the top of which is an electron-gun firing a stream of electrons towards a fluorescent screen at the bottom, in much the same way as a television tube works. This stream of electrons is focused by magnetic coils, just as light is focused by lenses, and the material which is to be viewed is placed at the point of sharp focus, much as in an ordinary microscope. The picture appears on the fluorescent screen at the bottom. This picture can be photographed and the photograph can be magnified about another ten times by ordinary photographic enlargement.

The maximum magnifications achieved in the microscope itself approach and occasionally exceed 100,000 times and consequently after the ten-times photographic enlargement, we achieve magnifications of about a million times.

In order to grasp what this tremendous degree of magnification means it is worth pointing out that if one took a penny and magnified it by the same amount it would be fourteen and a half miles across and would cover most of greater London.

The interior of the tube has to be evacuated of all air, since air

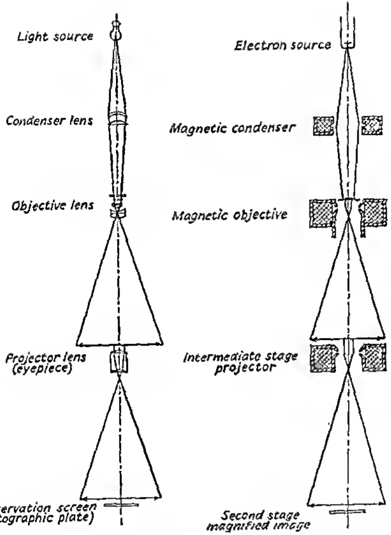


FIG. 4.—The Electron Microscope. The path of the electron beams is compared with the path of light rays in an ordinary microscope, here shown inverted, i.e. the eye would be placed before the eyepiece, as an alternative to the photographic plate.

would impede the passage of the electrons. In consequence the specimen to be examined must be placed in position by means of an air lock. This works on just the same principle as the air-lock used by men escaping from a submarine. The existence of this vacuum within the microscope also means that living specimens cannot be viewed. In fact, even dead materials tend to dry out, hence they may shrink or change shape, so that one cannot always be sure that what one sees is the same as it would be in life. Much ingenuity goes into methods of staining the specimen or shadowing it with fine metal particles blown on to it from one side so that its structure will stand out more clearly.

However, scientists have been studying the virus by other methods for many years and notably by two methods. Biochemists have analysed what materials it consists of by chemical analyses. Physicists have inferred a good deal about the structure by firing X-rays at the particles and seeing at what angles they were reflected—a method of investigation known as X-ray diffraction, as explained in the previous chapter.

I knew, therefore, that we would have to go to some centre of virus research which was also near a good electron-microscope, and one with enough room round it for a Television camera to work freely.

I therefore went to Cambridge and started by seeing Dr Markham, a biochemist, working in the Molteno Institute. He was somewhat sceptical of being able to say very much of interest in the few minutes which a television programme could allow him but consented to take part. He told me that the electron-miscroscope department at the Cavendish Laboratory had very recently produced some amazing new pictures of tobacco mosaic and turnip yellow mosaic virus which had never been publicly shown and which were being taken in September—it was now August 1958—to Berlin where they would be shown to the International Conference on Electron Microscopy. The photographs were truly wonderful, showing these viruses with far greater clarity, as well as much larger, than ever before; and they were very interesting from the scientific point of view because they confirmed many of the things which the scientists working with the X-rays had predicted—for instance, the fact that down the middle of the tobacco mosaic virus there should be a fine hole.

These photographs had been produced by a new technique devised by Drs Brenner and Horne—Brenner is a member of the Medical Research Council team which is working on the nucleic acids to which I have referred in talking about the DNA programme. I had thought at that time that he would make a good television performer but for various reasons he had been unable to appear in that programme. I was therefore very anxious to persuade him to appear in the new one and to explain his technique.

Brenner and Horne's special method for photographing virus consisted of spraying the particles with an ordinary nebulizer, or throat-spray, embedded in a mixture of heavy metal known as 'phosphotungstate'. This heavy metal stops the electron beam and thus provides contrast, as well as preserving three-dimensional structure at molecular level, for it collects more heavily in some parts of the specimen than others. The preparation of virus is placed upon a tiny screen, covered with an extremely thin film which will not stop the electrons. The object support is barely as large as a match-head, and the phosphotungstate is sprayed on to it. The specimen is then placed in the electron-microscope through the air-lock. (The devising of this technique was for Dr Brenner only incidental to his own work which is concerned with the study of the virus known as 'bacteriophage', referred to in the previous chapter.)

Dr Markham, by analysing viruses, has shown, as have other biochemists, that they consist of two substances only, protein and the mysterious molecules known as the nucleic acids. Actually, though the viruses which attack insects, and those which attack bacteria, contain DNA, most viruses seem to be based on RNA.

Actually, I have over-simplified in saying that there are only two substances, for Markham believes that he has found a third. These are minute traces of the so-called 'polyamines'. These are substances built out of the basic building-blocks of living material, the amino-acids. What function the polyamines fulfil is still unknown, but this very recent discovery has aroused much interest. It was here that we could bring out the extraordinary dual nature of the virus. We asked Dr Markham to hold up a small tube of tobacco mosaic virus crystals, maybe an inch in length; the clear, innocent-looking liquid in this tube was enough to infect a million tobacco plants. Then we put to him the leading question: 'Is the virus alive or dead?' All he could say was: 'It has some of the properties of animate and

some of the properties of inanimate matter. It is on the borderland of living and dead.'

Markham does much of his work by a delicate method of separation known as chromatography: he also uses a powerful ultra-centrifuge. The centrifuge is a device for separating the constituents of liquid when the constituents differ slightly in weight. In its simplest form it consists of little more than a crank and gear by which a test-tube can be whirled round and round, so that centrifugal force causes the particles in it to fly towards the outside. As the heaviest particles move fastest, the centrifuge can be used not merely to separate liquids from solids but even to separate out the substances in any mixture in order of their heaviness. In a high-speed centrifuge, the liquid is placed in a compartment in a rapidly-spinning flywheel.

The ultra-centrifuge carries this idea to new extremes. A chamber whirling round many hundreds of times a second in a vacuum creates centrifugal forces about 450,000 times as strong as gravity. Indeed forces of over a million g have been attained. These tremendous forces, which 'magnify' weights, are able to separate particles which differ in weight by incredibly small amounts.

Using this device on turnip yellow mosaic virus, Markham had found that he got, not one substance, but two substances of very slightly different weights. When he examined the two substances by spectroscopic methods, he found that the lighter solution has very little nucleic acid in it. From this he argued that it probably consisted of incomplete viruses—protein shells, lacking any nucleic acid core. This might be explained either by supposing that the process of making viruses had not been completed, or that the nucleic acid had escaped, leaving only the shell. Either way, the finding was consistent with the idea that the nucleic acid lies in the centre of the virus with the protein round it.

The photographs I had seen in the course of the afternoon had admirably proved the truth of this inference, for they showed that not only was the turnip yellow mosaic virus a kind of knobbly ball, but also that, when photographs were taken of the lighter fraction, one could sometimes see a small hole in the ball through which the nucleic acid might have escaped, or which might be the route of *insertion*.

While Markham was working on the biochemistry, the X-ray diffractionists were trying to determine the structure by their technique

in the Crystallography Lab at Birkbeck College, London. Professor Bernal was the first to apply it to tobacco mosaic virus, about a year after the virus was first isolated in pure form. This was a classic study, in the period 1937–41, but with the techniques available at that time, he was not able to do more than to show that the virus contained a sub-unit, while in 1954 Watson (the same Watson who, with Crick, proposed a structure for DNA) suggested that the pictures could best be accounted for by supposing that the structure was helical (i.e. like the thread of a screw).

In the early 'fifties Rosaliod Franklin (a brilliant woman research worker, who died recently at an early age) returned to the attack on the rod-like viruses, while Dr Klug specialized in the ball-shaped ones, such as turnip yellow mosaic. In 1955 Franklin completed the picture sketched by Bernal and Watson showing just how the helix must be constructed out of sub-units: there must be forty-nine sub-units in every three turns.

A minor puzzle was that the width of the virus, calculated from X-ray diffraction pictures, in which large numbers of viruses were being examined, was slightly less than the width as measured on electron micrographs of single viruses. It was realized, after a while, that this was due to the fact that each virus resembles a screw-thread. If a number of threaded rods are placed side by side, the threads of one mesh with the threads of the next, so that the centres of any two are slightly less than the width of one rod apart.

Markham had predicted that turnip yellow mosaic would turn out to be a sort of ball with nucleic acid inside: the work of a group of American X-ray diffractionists at Madison, Wisconsin, confirmed this. Klug and his co-workers extended the study from liquid material to crystals, and showed that the spherical shell was made of sub-units. Finally, in Brenner and Horne's electron micrographs, we can see for ourselves that this is actually the case. The predictions made by the delicate, indirect methods of the biochemist and the diffractionist are absolutely correct.

I knew that some impressive models had been made of tobacco mosaic and turnip yellow viruses, based on this work, for the Brussels World Fair, where they were shown in the International Hall of Science. I therefore specified for a short sequence to be brought from Brussels by the Eurovision link, and we persuaded Dr Klug to go over to Brussels to explain them.

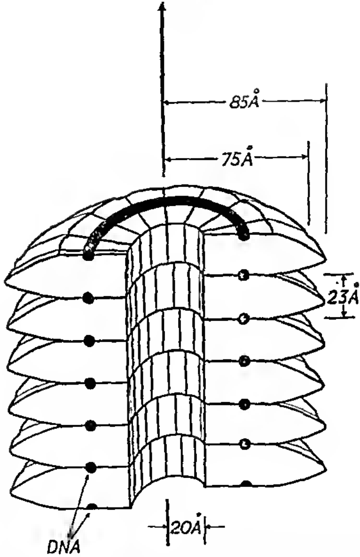


FIG. 5.—The structure of tobacco-mosaic virus, as it was revealed by X-ray crystallography. The virus is shown as if sliced in half vertically, and only six turns of helix are shown: it is much longer. The heavy black line and black circles represent DNA. The measurements are in "Ångstroms": an Ångstrom is a ten-millionth of a millimetre.

In much the same way as Dr Wilkins had explained his work on X-ray diffraction in the earlier programme on DNA, Klug started by showing the strange kind of picture which he gets when he shines X-rays through virus crystals. It is, of course, quite unlike the kind of picture you get when X-raying the human body, and the odd pattern is caused by the X-rays bouncing off the structure at different angles and sometimes reinforcing one another by landing on the same part of the photographic plate and sometimes cancelling one another out. By very complicated interpretations of these pictures, and calculations which call for the use of electronic computers, it is possible to arrive at a model of the structure.

The tobacco mosaic model was in the form of a rod standing vertically, but whereas the photographs only show a rod with a hole down the middle, the X-rays suggest that this rod is covered with knobs; each of these knobs is presumably a single protein unit and Klug lifted one of them out of the model to emphasize this point. If we look at the model as a whole we see there is a spiral (more accurately, helical) nucleic acid molecule. So once again we get the general pattern of a protein overcoat with a nucleic acid interior.

Photographs have recently been taken in which a 'pool' of unassembled protein sub-units can be seen within the cell, waiting to be assembled into viruses. It has also been shown that they will, in the right conditions, assemble themselves, forming an empty shell. These units are built up, within the cell from the amino-acid building blocks by the RNA, which acts as a template.

Thus the three lines of research all fit together very neatly. The electron-microscope pictures taken by the new technique show the structure of the protein overcoat, which fits in excellently with Klug's model.

Having established what the virus consists of, the next question is: how does it multiply? For this we went back to the Cambridge unit. Dr Brenner works, as I mentioned, with a special kind of virus which attacks bacteria, called a 'bacteriophage', and the electron-microscope had shown some time ago that it consisted of a head which appeared to have six sides and a tubular tail. Brenner had available a model of bacteriophage made from perspex. The model shows that the head is not simply six-sided, as might seem from the photographs, but is probably a box which actually has eighteen facets. In the centre of this box has been put a fine red string 100 metres in length,

for this would be the amount of DNA one would find if the bacteriophage were scaled up to be about 2 feet in length. It is in this 100 metres of 'string' that the information is somehow embedded which determines the production of this comparatively simple organism: we can imagine how much more complex the information must be when complicated organisms like the higher animals or man have to be constructed. The phage, and as described in the last chapter can be seen to approach bacteria, attach itself by the point of its tail and then squeeze out the nucleic acid contained in the head into the bacteria, the empty overcoat remaining attached to the outside of the bacteria. As Brenner said, it takes off its overcoat before entering the house.

The new photographs, however, showed a great deal more. At the highest magnifications one can see three little projections at the end of the tail and a number of fibres of hair-like structures: these are no doubt the organs by which it attaches itself to the coat of the bacterium. (It is also known that it carries an enzyme concerned with dissolving a hole in the bacterial coat.) Furthermore, the tail can be seen to consist of three tubes, one within another. In some of the pictures the outer part can be seen to have contracted, forcing the central part through the wall of the bacterium in the manner of a hypodermic needle. This is clearly the process by which the phage injects its nucleic acid into the bacterium—though how the nucleic acid is squeezed out into the bacterium is still a mystery.

The moral to be drawn from the behaviour of phage is that since the protein overcoat is left as a cast-off outside the bacterium then it must be the nucleic acid alone which has the power of creating new viruses and if this is true for phage it may well be true for other viruses.

Klug had pointed out that the nucleic acid is believed to act as a kind of template which determines the sequence of the amino-acids in the protein unit: in this case the nucleic acid of this phage seemed to be carrying out a similar role. As Brenner said, the phage is like the sort of city financiers who take over a company and instal a new Board of Directors in their own interests. The new Board of Directors sets the machinery to making new virus instead of making a bacterium as it did before.

Bacteria are very similar to living cells and this suggests that the way in which viruses attack the cells of our bodies or of plants

or animals may be similar to the way in which phage attacks bacteria.

I wanted at this point to show something of the extraordinarily ingenious work which is being done to gain understanding of the process by which the virus multiplies. It must be stressed that the virus is quite incapable of multiplying itself—it can only do so in the cells of some other creature. It is, as Brenner said, 'a genetic parasite.' It injects its own genes, or hereditary material, into the cell and thus changes the heredity of the cell into virus heredity instead of it having a bacteria heredity or, in the case of plants and animals, the heredity appropriate to the plant or animal concerned.

Thus the action of virus opens up basic questions in genetics—that is, the study of heredity—and in the whole process by which cells grow normally as a result of their normal hereditary components.

There are three experiments in this field which seem to me of particularly dramatic character. One of them was performed by two Americans, Fraenkel-Coorat aod Robley Williams. They showed that the protein and nucleic acid of the virus could be taken apart and that they, under the right conditions, would theo reassemble themselves into oew viruses. Surely there cao be nothing more strange thao the idea of a creature which can be taken apart and which can put itself together again? Once again we hardly know whether we are talking about a creature or a chemical process.

But they went further than this, using two strains of tobacco mosaic virus, which differ considerably in the assortment of amino-acids from which their protein units are constructed. Fraenkel-Conrat showed that you could put the nucleic acid of one strain with the protein of the other, and produce a perfectly good virus, which would behave like the virus from which the nucleic acid had been derived. The virus thus produced is about 50 per cent as infective as a natural virus.

Another major centre of virus research is the Max Planck Institute in Tubingen. Here two workers, Drs Schramm and Schaeffer, both had performed crucial experimeots. Like Fraenkel-Conrat, Schramm, who works with tobacco mosaic virus, had also separated the protein overcoat from oucleic acid and had then rubbed the nucleic acid on to the leaves of healthy tobacco plants. After a few days the symptoms of the mosaic disease appeared and the disease turned out to be precisely the same as was produced by infection of

the plant by the virus. In other words, nucleic acid alone can produce the same virus particles as the virus itself. This confirms the idea that the nucleic acid contains all the information necessary to the cells to regulate them so that they produce a virus. However, it must be added that the nucleic acid alone is much less infective than the intact virus: it takes an average of ten million particles to secure one infection. This is not surprising, for the virus has a hazardous journey working its way into the cell, and the protein coat no doubt serves to protect it from the many substances which might damage it.

Schramm has also shown that the separation of nucleic acid, which he achieved artificially, can occur in nature and is indeed the intermediate step in the formation of virus in the cell. As he told us, 'We shall be able to make a kind of working hypothesis that, as soon as the virus enters the cell, nucleic acid is released and that then the nucleic acid multiples and provides a template upon which a new coating can be built up, thus forming complete new viruses.'

Dr Schramm's colleague, Dr Schaeffer, deals with animal viruses and in particular has recently taken some rather striking photographs of a virus which causes a heart disease in hens. This virus also releases its nucleic acid into the cell in the way which has already been described. What Schaeffer has done that is new and interesting is to find a way of staining the two components—the nucleic acid and the protein—with a fluorescent dye, so that one can trace their movements within the cell.

'By this technique,' he said, 'we can show that at first the nucleic acid turns up in the nucleus of the cell.' And he produced a vivid photograph in which the cell nuclei could be seen to be glowing with fluorescent light. Somewhat later, he explained, one can detect the other component—the protein—distributed through the cytoplasm, or outer part of the cell. In other words the virus has again taken itself apart, the nucleic acid has migrated to the nucleus to do its work, while the protein has remained in the outer part of the cell.

Later still both these components seem to migrate to the outer part of the cell, near the outer wall, and it seems to be here that the new viruses are formed. This fowl-virus seems to have a rather more complicated structure than the ones we have been considering in this programme, and perhaps in more complicated cases the process of reproduction may be more complicated too.

It would seem very difficult to find any way of preventing this kind of multiplication process within the cell without damaging the cell itself, and hence very difficult to find a new way of curing virus diseases. Nevertheless this is just what Dr Alick Isaacs and Dr Lindemann seem to have happened upon. At the National Institute of Medical Research at Mill Hill they work with viruses which cause disease in man and in particular with the influenza group of viruses. (Influenza is of several types, which vary in virulence.) Isaacs started from a fact which had been known for twenty years at least: that if a cell is attacked by two different kinds of virus simultaneously, they interfere with one another and the disease does not develop. (Using our metaphor of the Board of Directors one might say that two Boards of Directors start fighting with one another and consequently have no time to run the company at all.)

Furthermore, if cells are infected with virus which has been killed in a particular way the cells are no longer able to support the growth of live viruses. This is known as the 'virus interference phenomenon'; it only occurs if the virus is killed by ultra-violet light from a narrow range of energies. No one, however, had made any practical use of this discovery.

Isaacs and his colleagues found quite recently that the killed virus was not in fact completely inert, but that it produces a substance within the cell which they named 'interferon'. The interferon produced by cells inoculated with killed *influenza* virus also proved able, when inoculated into fresh cells, to prevent the growth of a number of other kinds of virus. It therefore became important to try and get hold of interferon in the pure form so that they could find out how it acts, and see if it could be put to any practical use.

Influenza virus is grown in hens' eggs—not the sort that come to table but fertile hens' eggs. This is because, as already mentioned, no virus can grow except in the cells provided by some living organism. On the screen we were able to show Dr Isaacs's assistant, Mr Law, 'harvesting' the eggs—removing from them drops of the virus—each drop containing 1,000,000,000 virus particles. We then could show him killing the virus by exposing it to ultra-violet light from quite an ordinary ultra-violet lamp.

The next step is to mix the newly-killed virus with some kind of living cells. It is convenient to use as a source of cells the membrane that lines the shell of an egg. One simply cuts off the end of the egg,

pours out the yoke and white, and then with a pair of forceps pulls out the membrane lining the egg. It is known as the *chorio-allantoic* membrane. The membrane is rinsed in salt solution, then put in a bottle along with some of the killed influenza virus. The two are allowed to cook together in a hot room and over the next three days the resulting fluid is collected. What is happening during this period is that the *killed* influenza virus is entering the various cells, and, after an interval, they begin to produce *interferon*. This, of course, is in striking contrast with what would happen if *live* influenza virus were to enter the cells—in this case more *live influenza virus* would be constructed.

Isaacs and his colleagues have found that interferon which is grown in this way prevents the growth of a large number of different viruses without showing any visible damaging effect on the cells. It even prevents the growth of the virus which we use for vaccinating people—known as the 'vaccina' virus.

Clearly, therefore, interferon looks very interesting as a weapon for attacking virus diseases generally. We may think of it as a kind of antibiotic which could be used against viruses

Before interferon can be tested on animals, and ultimately on human beings if this proves safe, it will be needed in pretty large amounts and by some kind of modification of the methods just described it should not be too difficult to produce enough.

It should be added, however, that it is first necessary to purify the interferon. This is done by a rather lengthy method known as 'ion exchange chromatography'—much the same method as Dr Markham was using for research purposes. The liquid to be analysed is passed through resins selected for their powers of attracting different substances to different degrees. The conditions in which the interferon sticks to the resins throws a good deal of light upon its probable structure. Present experiments suggest that it is a protein—which is, of course, what we would expect.

Finally we come to the question: how does interferon act? Now the interesting thing is this: if we introduce live virus into cells which have been treated with interferon the cells produce instead of more live virus, more interferon. It seems, in fact, that interferon has taken over the cell factory to the extent that it dictates what the factory is to produce, although by itself it is not capable of starting off the actual production. So when live virus subsequently enters the factory,

production starts off along the pattern set off by the interferon and not along the pattern set down by the virus, as it would normally; neither does it follow the pattern which the cell would have if it had not been infected.

In all these cases what we see is the cell machinery receiving some kind of instruction which determines what it will produce. This instruction is, scientists believe, conveyed by the nucleic acid: and it is because the virus introduces a different nucleic acid conveying different instructions that the cell is perverted into producing a different kind of product from what it normally does. (While in the case of interferon it is perverted yet another way into producing more interferon which fortunately is not, from our point of view, as bad as if it were to produce more influenza or some other kind of disease.)

As Dr Isaacs ended by pointing out, this makes one more hopeful about the chances of using interferon as an antibiotic. It is always much easier to use a drug effectively if one has some idea how it works. But the behaviour of interferon seems to have a wider significance than this. For if it is possible to introduce false information into cells and to make them do things they would not normally do, then it may be possible one day for scientists knowingly and deliberately to introduce information into cells and to make them do things they want them to do.

This holds out the prospect of quite extraordinary ability to control growth and development processes and even what we normally regard as the direction of heredity. This is the same theme which we were discussing in the DNA programme. Since the most widely-known case in which growth processes go astray is that of cancer this whole line of research is very relevant to the possibility that scientists may finally, after so many disappointments, find a method of dealing with that disease. While it is too early yet to tell what direction future experiments will take, there is not the slightest doubt that scientists have opened up a chapter of quite extraordinary interest in the research field—the potentialities of which are past human estimation. The pace of work on this subject is rapid. In Europe and America, as in some other countries, work is going on every day on many aspects of this subject.

Even since the programme was broadcast, Horne and Brenner have pressed on to produce equally remarkable pictures of the viruses of poliomyelitis, and herpes—a virus which causes 'cold

sores' on the lip and elsewhere in human beings—while Klug has worked out all the possible ways in which protein sub-units can be assembled to form the ball-shaped viruses, and has determined the exact shape as an icosahedron, or figure bounded by twenty equilateral triangles. We can be sure that in another year or two there will be more to report on this subject.

Since the above was written Dr Isaacs has come to regard the mechanism by which interferon is produced as a natural celluar defence mechanism, quite distinct from the blood-borne immune mechanisms on which we rely for recovery from many bacterial diseases and in vaccination. If he is right, these are the first gropings towards a whole new area of medicine which may one day make it as easy to control virus diseases as it is to control bacterial diseases to-day.

8

Up in the Clouds

In a London laboratory, scientists reproduce the processes by which rain and snow are made inside clouds.

MOST of the rain which falls on us in this country comes from melted snow, formed thousands of feet up in the clouds, which has melted on the way down. This simple fact has only recently been definitely shown by scientists, who are exploring what goes on inside clouds—a subject known as cloud physics. To be more exact, cloud physics is the study of the processes involved in the formation of clouds, and of how snow, rain, hail, lightning, etc., are developed inside them. This is a specialized branch of meteorology, which is the science which studies how large masses of air move round the world, and how their temperature and humidity (amount of moisture carried) varies—factors which cause the changes which we know as 'the weather'.

But cloud physics, of course, also contributes to understanding the weather, and may even provide some aid in controlling the weather one day, for it is closely connected with the attempts to make clouds release the moisture they contain as rain which have been conducted in the USA, Australia and other areas affected by drought.

What goes on in the interior of clouds is still pretty mysterious, for it is difficult to study. One can send up an aeroplane into the middle of a cloud—where it may be (in the case of thunderclouds) in some danger from the powerful upward draughts of air—but its very presence, and the hot gases from its engines, may alter conditions inside the cloud, at least in the neighbourhood of the aircraft. And since it cannot stay still, the men in it cannot study such processes as the development of a single drop of rain or the growth of a single ice crystal.

And these are among the central mysteries which cloud physicists

wish to involve. The big advance which has taken place in recent years is that ways have been found to reproduce in the laboratory, in miniature, many of the processes which occur within clouds. Hence it is now possible to study precisely the conditions which govern such processes and to measure the effect of small changes in them.

It is only since the war that scientists have really got down to these problems, and there is in Britain at present only one laboratory devoted solely to this subject as a whole: it is at the Imperial College of Science and Technology in South Kensington, and was set up about nine years ago by Dr B. J. Mason. (Work on the physics of clouds has however been done in the Physics Laboratories at Oxford and Cambridge, among other places.) This lab is building up a store of information which is providing an answer to some of these questions, and so I went to see Dr Mason to discover whether the work there could be presented effectively on television. There were many technical difficulties in presenting the material—I describe some of them in another chapter. Apart from the purely technical problems, some of the demonstrations could not be relied upon to take place at a given moment—one had to wait for ice to build up when it was in the mood to do so. Other processes were very slow, for instance the growth of ice crystals themselves, so that it would be necessary to use speeded film to show them occurring at all.

However, there was some film already available, and particularly a rather beautiful film made by the Japanese physicist Nakaya, showing the growth of ice crystals. One can see how these six-sided crystals proceed to add small sections in a series of leaps. The sections all have sides which slant at sixty degrees, so that the screen gradually becomes covered by a tracery of strange shapes, looking like some abstract picture.

Dr Mason had one demonstration which made the main point very effectively—that is, the point that he is trying to duplicate in his laboratory processes which normally go on miles up in the sky and on such a titanic scale that it is very difficult to study them.

Mason has devised a very ingenious method of showing the way in which a cloud develops. This consists in obtaining a glass tank of very clear water, which is allowed to become completely still, and then upsetting into it a ladle full of white liquid. This liquid expands in the typical cauliflower shape which one sees in a cumulus cloud. So we decided to run some speeded film of cumulus cloud develop-

ing and then immediately to follow it by this demonstration, so that the similarity would be obvious. Mason's cloud developed from the top downwards, of course, but it was possible to turn the image upside down electronically after it left the camera and so to make the similarity very obvious.

The first question naturally is: what does a cloud consist of? It consists, when it is not engaged in raining, of countless drops of water; it is in fact the same as a fog. The droplets of water are less than a thousandth of an inch across and are invisible to the naked eye. The problem is how do they turn into raindrops which are much larger? The answer is that they freeze—or rather, that ice crystals begin to grow, drawing on the water droplets for raw material. How and why does this occur?

The point about these drops is that they remain liquid even when the temperature is well below the normal freezing-point of water—as much as −15° C. (On the centigrade scale 0 equals freezing and 100 equals boiling-point). The droplets are therefore said to be *super-cooled*. Mason showed me this quite clearly by breathing into a refrigerator which had been kept at well below freezing for some time. I could see the moisture in his breath condense immediately into a fog. The question is then; why don't these droplets freeze? The answer is that they require the presence of tiny particles, known, generally, as ice nuclei, on which to start the process of forming ice crystals. A crystal cannot begin to form unless it has something on which to anchor itself, and to build up from.

The transformation from super-cooled droplets into ice crystals can be shown by breathing into a refrigerator—thus producing a 'cloud' of moisture—and then scattering some particles of 'dry ice' into it. Within a few seconds the cloud becomes full of glittering points—ice crystals which have developed from myriads of small droplets which have become frozen by the intense cold of the dry ice.

When ice crystals form in an ordinary raincloud, however, it cannot be ice which provides the nuclei—it is, in fact, tiny particles of mineral dust. Where these particles come from is still a matter of controversy but Mason believes, on the strength of recent work, that they are particles of mineral clays and volcanic ash.

In order to bring the observation of this process within the scope of the laboratory some special technique was needed and Mason had

hit upon a most ingenious method which brilliantly demonstrates the ingenuity the scientist so often displays in finding a very simple way of solving a fundamentally awkward problem. His problem was to seize the moment at which a crystal begins to grow on one of the countless invisible particles floating in the air. He therefore needed something which would trap the particle and hold it in one place so that it could be examined; and at the same time something which would facilitate the growth of the crystal if possible, so that it would reach a size at which it could be seen quite quickly. What occurred to him was to make a soap film by taking a wire ring and dipping it in a solution of detergent, just as if he were going to blow a bubble—and in fact for this purpose he simply used the detergent which he found in his wife's kitchen where it was used for washing-up purposes.

On dipping this ring into the cool air in the refrigerator and waiting a few moments one begins to see crystals starting to form at many points in the surface of the film; they grow visibly under the eye until the size of a shilling or larger. I say the size of a shilling but of course they are not circular; their edges consist of many little straight surfaces and one side will grow faster than another so that the shape is not symmetrical. What happens, of course, is that the tiny clay particles land on the soap film and are trapped and at the same time the soap film facilitates the growth of the crystal and provides a support for it.

To recap, the rain-making process is as follows: water vapour is drawn up (evaporated) from the earth's surface by the heat of the sun, and is carried aloft by the air currents until it condenses into droplets like those one sees on breathing into a refrigerator. These droplets become super-cooled by the presence of colder air but they do not freeze until they meet nuclei.

The next step in the story is to examine the process by which droplets sometimes freeze. At this point in the programme we brought in a colleague of Dr Mason's, Mr Maybank, a Canadian physicist employed by the Canadian Defence Board but attached to the cloud physics laboratory here. To examine this freezing process, a single drop of water is placed on a wire which is in fact a small and accurate thermometer; then it is lowered into a cold chamber. This chamber is cubical in shape and only a couple of inches in each direction. It has two glass sides so that the fate of the drop of water can be observed

above and warmer below. The chamber represents a cloud upside down, so to speak.) Water diffuses into this chamber from the top. A long nylon fibre is suspended vertically through this chamber. On this, ice-crystals gradually form. What has interested and surprised physicists and crystallographers is that the shape they take varies with the temperature. At the top, in a temperature range of 0 to −3° C., the fibre is seen to be encrusted with flat six-sided disc-like crystals. An inch or so lower, where the temperature is −3 to −8° C., the shape changes to needle-like crystals which stick out from the fibre in every direction. Below this again one can see hollow six-sided columns growing from the fibre. Farther down again (from −8° C. to −12° C.) a system of little plates which gradually grow more complex until elaborate fern-like shapes are seen. At this point the structure is at its widest and as we proceed still lower (−16° C. to −25° C.) we see more plates and finally (below −25° C.) columns again. Thus there are five changes of shape within some twenty-five degrees change of temperature (See Plate 10).

This is an extraordinary thing, for no similar changes take place, as far as is known, with any other crystallizable substance, and the discovery that this change is due exclusively to change in temperature is something new. It was formerly supposed that it was due to changes in humidity, i.e. the amount of water vapour present in the air.

That these changes are due entirely to the temperature change can be shown by shifting the fibre vertically, so that—for instance—the plates are now in the region which previously grew columns. If this is done, columns immediately start growing out of the corners of the plates, with corresponding adjustments in all the other zones of the fibre.

'Why the crystals should take these different shapes is still a mystery on which the department is working,' Mason says. He has one clue to start from: the fact that ice crystals prefer a six-sided shape in which the angles are always sixty degrees. This can easily be explained by reference to the atomic structure of the crystal, which has been established by the X-ray diffraction technique I have referred to in earlier chapters. The atoms in a crystal of ice consist of alternate hydrogens and oxygens arranged in the sort of open-work structure which is called a *crystal lattice*. If this is looked at from the end it can be seen to be formed into six-sided rings which adjoin one another just like the cells in a honeycomb. Seen at right angles to

this direction one observes simply a complex lattice. It is this built-in six-sided character which ensures that the ultimate shape is always six-sided and that the opposite sides are always parallel.

The crystals seen in this demonstratioo took some twelve hours to grow and since, if growth continues too long, the demonstration breaks down, it was necessary to start the growth process at nine o'clock in the morning, in order that the 'tree' should be fully grown in time for the transmision in the evening. We arranged for the provisioo of a special industrial television camera fitted with an ex-stension tube containing lenses to magnify this small structure, in an attempt to bring to the viewer the beauty of this extraordinary 'Christmas tree' of strangely-shaped ice-particles. This one shot thus cost the BBC some £80.

To bring out the way in which crystals form by the constant addition of water molecules on this six-sided framework, we here made use of the film prepared by Professor Nakaya to which I referred at the beginning of the chapter.

To sum up then: the rain-making process normally consists of the formation of ice crystals which grow into snowflakes, the snowflakes becoming too heavy to stay in the upper part of the cloud fall out of it into warmer air where they melt and turn into rain.

The fact that the change in crystal shape is due to temperature has beeo beautifully confirmed by sending aeroplanes into the clouds to collect crystals at various altitudes. They have io fact collected crystals of all the types described and these changes of shape occur with change of temperature just as predicted, so that the two-foot chamber in the Cloud Physics laboratory effectively represents a column of air running up to some 45,000 feet above the earth.

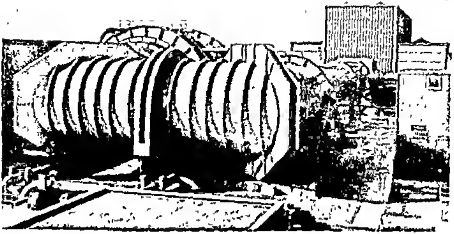
Another need for the student of cloud behaviour is to know when this kind of development is actually taking place and he also wants to know precisely at what height the various parts of the process are occurring, for this might turn out to be significant, or to be a useful tool in the prediction of weather. Radar, it has been found, can provide the answer to this problem by sending pulses of radio waves up into the sky to be reflected by rainclouds. Mason showed on the screen of a cathode-ray tube how he sees what is happening a mile or two above his Kensington laboratory without moving from his lab. Radar aerials on the roof of the College send out a beam of radio

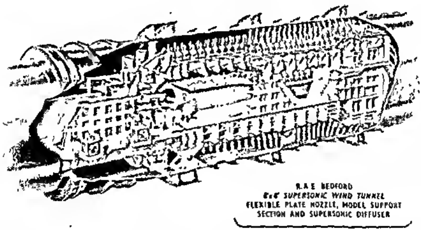
pulses which sweep back and forth over a semicircular slice of sky—a vertical slice. The melting snow returns a strong echo and a solid line is drawn across the screen at a height proportional to the height at which this is occurring. The screen itself is marked out in semicircles which represent heights of 10,000, 20,000, 30,000 feet, etc. On the night when we were showing the programme the level of melting snow could be clearly seen at about 5,000 feet. Down in London it was raining drearily but not heavily — we hoped for a really bad night for once so that this demonstration would be clear! In favourable conditions one can also see a second signal from higher up where the snow is forming.

This kind of research is already beginning to throw light on rain-making, which has up to now been done very much on a guesswork basis. The technique employed is to look for a cloud which is on the verge of raining but unable to do so because insufficient ice nuclei are present. An aeroplane then flies over the cloud and shovels out quantities of 'dry ice'—or solid carbon dioxide—which produces large numbers of ice crystals by chilling the cloud to a very low temperature—about −70° C. In very favourable conditions when the cloud is just on the brink of forming rain this may have the effect of tipping the balance. Of course it is difficult to be sure that the cloud would not have rained in any case and it is only by doing the experiment a large number of times and seeing how often it is successful that one can build up any knowledge on the subject. Scientists still know very little about this.

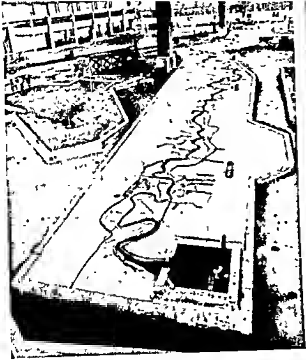
The process can, however, be shown in the laboratory quite easily by dusting dry ice into a refrigerator in which a cloud has been artificially produced by breathing into it in the way already described. First, one sees white trails left by the dry-ice particles—trails which rather resemble those left by aeroplanes travelling at great heights and known as 'contrails' or condensation trails—although the exact method of formation is not quite the same. A few seconds later the refrigerator can be seen to be full of brilliantly-sparkling ice crystals; this is quite a striking demonstration and the whole thing glitters like some Christmas toy. At the bottom of the refrigerator one would find, if it were two miles deep and not two feet deep, a miniature snowstorm.

As the reader may remember, another substance which has frequently been used in attempts to cause rain to fall is silver iodide.





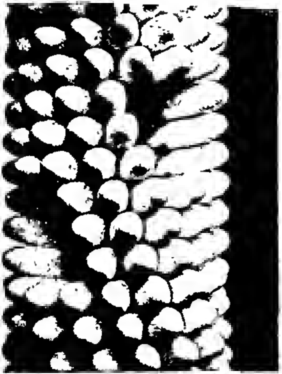
The high-speed wind-tunnel at the Royal Aircraft Establishment, Bedford 1 An exterior view; and 2. the working section. A technician can be seen adjusting an aircraft model, which is supported on the 'sting' Behind him, to the right, is the adjustable 'throat' and above and below it the array of jacks which control its shape



4. The model of the tidal reaches of the River Trent, looking downstream from Newark, on which flood control was studied. On the extreme left two men can be seen revealing the huge size of the model. (Scale 1:800)

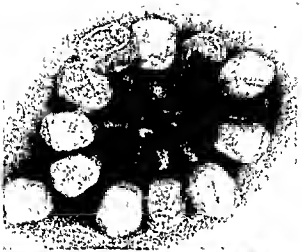
3. One of the minature current meters which measures the speed of water-flow in the models of rivers at the Hydraulics Research Station.

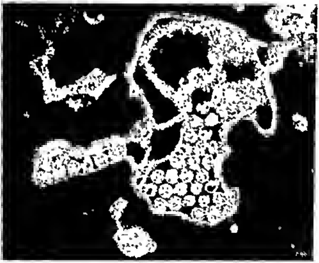
5. On the subject's head is a television camera which reports his field of view, while the electrodes around his eye detect faint electric currents which are produced by his eye movements. The output of both is fed to a television screen upon which appears both what he *could* see, and what at the moment he is actually looking at.



7. The model of tobacco-mosaic virus, conceived by Dr. Klug, and shown at the *Brussels World Fair* in 1958.

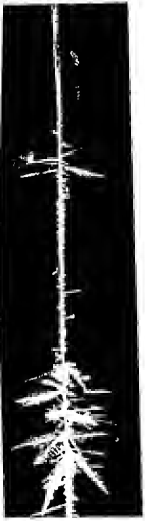
6. The thread of life—a model of the unique molecule deoxyribose nucleic acid, which lies within the nucleus of every living organism, plant or animal, and determines its hereditary characteristics.

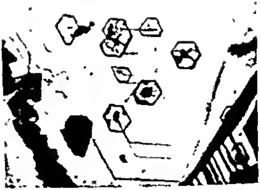




8. Bacteriophage possesses a contractile sheath round its probe, and thus forces the probe through the cell-wall to which it is attached. Seven of the sheaths can be seen to be contracted in this remarkable photograph. (x 200,000)

9. Poliomyelitis virus particles; they appeared in a cell 5½ hours after it was infected in a laboratory experiment. In the top half of the picture can be seen masses of protein sub-units not yet assembled into complete viruses. This is the first time this has been seen, and this picture has never been published before, (x125,000)

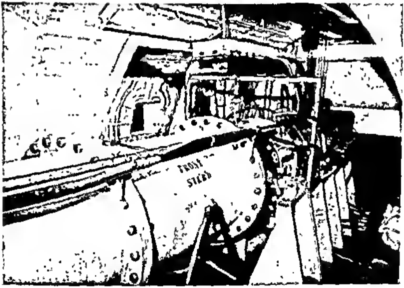




10. The 'tree of ice-crystals grown by Dr. Mason The upper end of the thread was at about O° Centigrade and the lower end at about −18 Centigrade. Note how the crystals change in shape from discs through needles and six-sided hollow columns to fern-like shapes; and finally to plates. (x2)

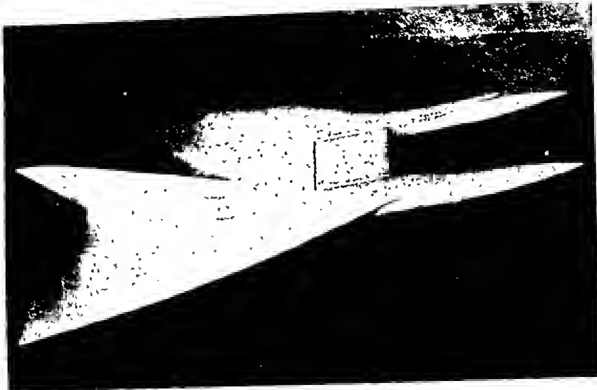
11. *The ice-coated water droplet thrusts out an icy protuberance* before it shatters. (x15)

12. The six-sided structures, bounded by a dark line, are ice crystals; they are growing on a crystal of cadmium iodide, the steps in the surface of which can be seen as a spiral line, with the snow crystals situated on the line and at angles in it, thus fulfilling Dr. Mason's prediction (x150)

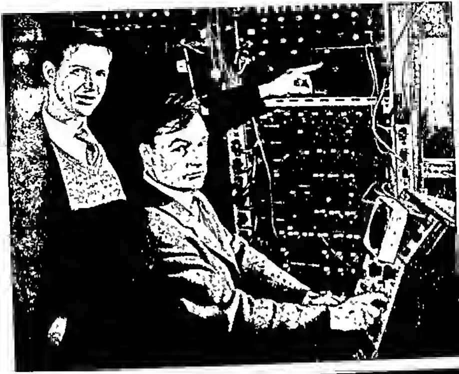


13. Engineers at the main control panel looking into the test-cell, the far wall of which has been raised for adjustments. The drum-shaped object (*centre*) is the nozzle of the ram-jet.

14. Inside the ram-jet test-cell of the high altitude test-plant. Air, at great pressure is blown through the large tube into the ram-jet motor. A window of the control room is seen left of centre.



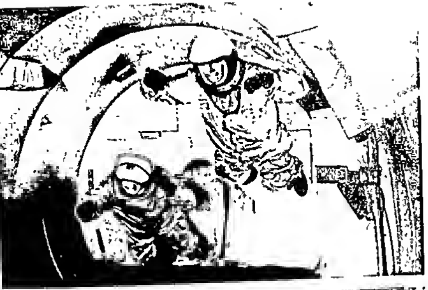
15. *Supersonic* airliner with combined ram-jet and turbo-jet power-plants suggested by Bristol Siddeley Engines. It is designed to cruise at 2,000 m p h. (3 times the speed of sound) and would carry 150 people from London to New York at the same cost as present-day piston-engined airliners. Moreover, it could use the same airports.



16. Mr Strevens and Mr Anthony with "PAT".

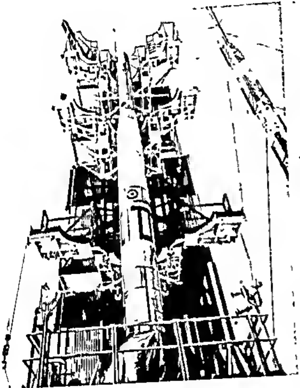
17. A photograph of the pitchmeter display: the lower boundary of the bright area traces the changes in pitch in the sentence 'Yes . . . I think so".

18. The Black Knight rocket-motor as it was shown to the public or the first time in *Breakthrough*, with Raymond Baxter. Note two of the movable discharge tubes at the bottom.

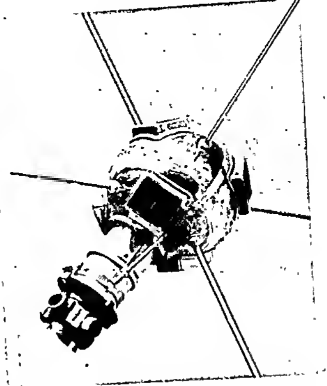


19. Man undergoes the experience of weightlessness! United States airmen float in an aircraft flying on a curved path calculated so that centrifugal force just balances out gravity.

20. A test pilot adjusts the eye-camera which films the movements of one of his eyes as he straightens out after a fast roll.



21. Vanguard first and second stages on the launching pad at Cape Canaveral. The three pairs of decks can be swung round to enclose the rocket for servicing.



22. Test satellite mounted on the nose of the third stage of the Vanguard rocket at Cape Canaveral. The six rectangular objects on the surface are devices for generating electricity from the sun to power the radio transmitters.

The Cloud Physics laboratory has explored why silver iodide should be so effective in speeding the formation of ice crystals. It finds that the surface structure of the iodide crystal is very similar to that of an ice crystal, so that the water vapour attaches itself to the iodide, as a result, one might almost say, of being fooled into supposing that it has got an ice crystal to attach itself to.

Mason demonstrates this with the aid of a special microscope which has been fitted with a cold chamber in place of the usual stage on which the slide is mounted. This small box, which has a glass top and bottom, is chilled by pouring in through a funnel a little liquid air, and it contains some silver iodide crystals. When I looked through this microscope I could see forming on the surface of the silver iodide small crystals, and these were expanding in a series of jerks, in just the same way as the ice crystals in Nakaya's film. I noticed that these crystals are six-sided with sixty-degree angles, as we should expect, and furthermore these crystals are so arranged that their sides are parallel. This is because they fit themselves on to the underlying structure of the silver iodide crystal and so they all become lined up in the same way. What could not be seen on television is that beautiful colours are produced by light interference, in much the same way as colours appear in a thin film of oil when it spreads on water or a road surface, and as the crystals grow in thickness these colours change in hue. From this, in fact, the thickness of the crystal can be estimated with great accuracy.

Since the programme was broadcast Mason has devised an ingenious verification of the interpretation he puts upon these observations. He reasoned that, if snow crystals can be induced to grow upon a crystal, the flat two-dimensional surface of which has the same pattern as a snow crystal, they should grow even better on a crystal which had a similar structure in three dimensions. Cadmium iodide proved to be such a crystal. It develops in a series of steps—seen from above the edge of the steps forms a rough spiral (see Plate 12). If Mason's view were correct, one would expect the snow crystals to form only on the 'steps', and in fact at the bends in them. Mason therefore tried the experiment of growing snow crystals on cadmium iodide, and, as the plate shows, his predictions proved correct.

Despite these first steps towards the artificial production of rain, it is quite clear that very many years will pass before rain-making can

be achieved at will and still more before the weather can be controlled on the grand scale if, indeed, this ever occurs. At present all we can do is wait for a situation where rain is on the verge of falling and try just to tip the balance; we cannot possibly produce clouds where none exist, nor drive them away when we do not want them.

It is often asked whether the hydrogen-bomb tests could affect the weather and the bad summer of 1958 in England caused many people to wonder whether this was due to nuclear tests. However, the north of Scotland had an exceptionally good summer so that there was really no justification for this idea unless—as one facetious writer to the papers suggested—the rain now only falls on the areas of full television coverage. In point of fact the energy which the atmosphere absorbs from the sun is equivalent to that released by one hydrogen bomb every second and therefore even these titanic explosions are of trivial significance in relation to the world weather. This, at least, was as far as Dr Mason was prepared to go: though, of course, the mere supply of energy to the atmosphere is not the only factor in weather formation. For instance, as is well known, a volcanic eruption may produce effects which are visible in the sky for many months after an eruption because they release many small particles into the air.

The study of weather-forecasting and weather-control is arousing increasing interest among military authorities because if ever it were possible to bring on or to dispel clouds then considerable damage could be done to the enemy, and his attempts to organize a war could be hampered. Indeed we have reached the point at which much weather-research is 'restricted' information.

The process whereby ice crystals form on tiny particles of clay is called nucleation and it has recently been realized that this kind of process is important in many other fields. For example, the reason that uncalcined gypsum is added to plaster of Paris in order to accelerate the setting of the plaster is that it provides nuclei for the purpose. Builders have long known that this was a good thing to do but it has only recently been realized that this was the reason. Another fairly well-known example of nucleation is the Wilson cloud chamber used by physicists. This is a small chamber which serves to reveal the tracks left by high-energy particles, such as electrons and protons and alpha-particles. As the high-energy particles pass rapidly through the chamber they knock electrons off molecules

of air which are present and these form nuclei on which water vapour can condense, thus leaving a trail of droplets rather similar to the condensation trails left by aircraft in certain conditions, but of course very much smaller. This provides a good example of how work in one scientific field often profits from work in some quite different field.

In the same way, the work of cloud physicists should not be judged simply as an attempt to deal with a particular set of problems—the formation of rain, and so on. It is at the same time the exploration of basic processes in nature. Research on basic practical problems almost always uncovers the need for more understanding of basic processes, and countries which neglect their 'pure' research soon find themselves lagging behind in fields of applied research.

As this research continues, new points continually come to light. For instance, Mason and his co-workers have recently found that the forms which crystals take when they grow in the experimental chamber are altered if certain impurities are present—such as camphor or alcohol. Only minute traces of these impurities are enough to produce the effect. Why they do so is still being explored.

From work such as this, and that of students of crystal growth from quite different aspects, a science of controlling crystal growth is gradually beginning to loom in sight. Such control has been used in practical circumstances for many years without the explanation being understood. For instance when ice-cream is churned or when fudge mixture is beaten the real object is to promote the formation of numerous fine crystals. This kind of information may also help engineers to control the formation of ice in hydro-electric plants. The ice from the reservoir can be kept out but it is more difficult to prevent ice forming in the actual interior of the pipes and turbines when the water is extremely cold. This ice not only obstructs the water flow but if bits break loose they may damage the turbine blades. It is even possible that the study of nucleation may throw light on the cause of cancer, some types of which seem to be started by the arrival in the lungs or elsewhere of very small particles contained in industrial smokes. Whether these particles have a purely chemical action or whether they act as nuclei for the growth of crystals is at present a mystery.

Research is a process which has no end. Each discovery opens up a new set of problems.

One interesting thing which has arisen out of the work of the cloud physics lab is the fact that scientists really know very little about the composition and properties of water—ordinary water. Water is a strange substance in many ways—for instance, it expands on freezing whereas all other substances contract. In school books we are told that the formula for water is H_2O: but in fact it seems unlikely that the atoms are arranged in these neat pairs, and certainly this is not so in ice. Some molecules are split up into segments carrying electric charges—that is to say, into ions. Besides, the behaviour of water is also affected by minute traces of impurities. Dr Mason has therefore been organizing a comprehensive research into water and all its properties; physicists, chemists, crystallographers, meteorologists and others will pool their information.

Up in the Clouds was a further example of pure research. In the next chapter we return to applied research into a practical problem, but this time financed, not by the State, but by private enterprise.

9

The Flame in the Wind

London to New York in two hours is the objective of those who work in this £1,000,000 test plant.

As I walked down the broad road which runs into the ram-jet experimental establishment of Bristol Siddeley Engines Ltd. I could see a number of enormous buildings widely scattered. Into some of these ran huge tubes, while a vast chimney, the size of a big grain-silo or a water-tower, rose behind one of them. There was a faint whine in the air and as I passed the corner of one of the buildings this rose to a scream. The air seemed to tremble and there was a kind of thudding sensation at the back of the neck. I was conscious of being in the presence of tremendous power.

I had come to see the work being done on developing the latest aeronautical power device, the ram-jet. By a coincidence the papers that morning had carried the announcement, based on a statement by Dr Hooker, one of the Technical Directors of Bristol Siddeley Engines, that before long we should be able to fly to America in *two hours*, in aircraft which would rely on ram-jets for the high-speed part of their flight but which would use ordinary jet engines for take-off and landing.

It was this development which I had come to explore, although the appointment had been arranged some time before the newspaper story.

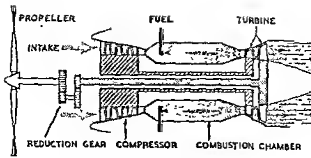
Ram-jets already provide the power-source for the Thor ground-to-air missile and give it speeds of two or three times that of sound—as engineers say, speeds of Mach 2 or Mach 3. As explained in Chapter 2 (p. 9) Mach 1 indicates the speed of sound, Mach 2 twice the speed of sound, etc.

The ram-jet is a very simple device. It consists basically of little more than a tube into the front of which the air rushes as it flies

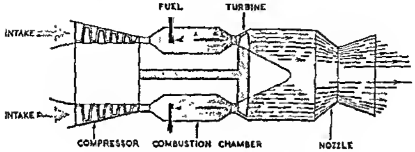
forwards. Into this airstream fuel is injected and set alight so that it burns, producing volumes of additional gas. This gas, combined with incoming air, rushes out of the the tail at high speed producing a forward thrust on the tube. In this respect it resembles a rocket or a jet engine. Both depend on the basic principle that every force produces an equal and opposite reaction. A man floating in space, where friction would not impede his movement, could propel himself by throwing away his personal belongings: they would go in one direction, he in the opposite. The weight of what he threw times the speed at which he threw it would equal his own weight times the speed at which he would be propelled in the opposite direction. (He could even propel himself by spitting.) So also the speed of a rocket, in the vacuum of space, times its weight equals the weight of the ejected gases times the speed at which they were shot out. In the case of a ram-jet, operating in rarefied air, the propulsive effort will be proportional to the weight of the gases times the speed of ejection. The difference between a rocket and a ram-jet, or indeed any jet, is that a rocket derives all its gas from the fuel or propellant, whereas the jets make use of the available air, adding only a little fuel to it—a more economical arrangement.

A ram-jet then, consists of little more than a specially-shaped tube with some fuel jets. It has been called a flying stove-pipe. But of course it only works when it is already moving forward, since when it is still the air does not rush into the front. In fact, until it is going at about the speed of sound, the air is not rushing in fast enough for it to work. That is why in the ordinary jet engine which works on basically the same principle, a huge compressor is necessary to build up a sufficiently high pressure in the combustion chamber, where the fuel is burnt.

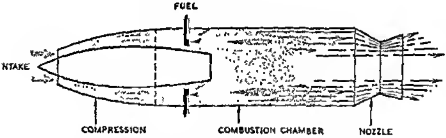
This compressor gets its power from a turbine placed in the exhaust tube of the jet so that the outgoing gases, besides providing the whole structure with a forward push by reaction, drive the turbine, which is on the same shaft as the compressor, and so the latter forces the air in. (See Fig. 6). It is also possible to place on this shaft a propeller, so that some of the thrust can be derived from it, as in a conventional aircraft: in this case the power-plant is called a turboprop. The faster you go the less effective a propeller becomes: it fails to bite the air, which cannot flow in fast enough. But the faster you go the more effective the stream of gas coming out of the back



TURBOPROP



TURBOJET (PURE JET)



RAMJET

Fig. 6

Turboprop. The burning gases drive the turbine, which in turn drives the compressor which forces in more air for burning. The turbine (either the same one which drives the compressor, or a different one as shown here) also drives the propellor, which provides most of the propulsive thrust.

Turbojet (pure jet). The burning gases drive the turbine, which in turn drives the compressor which forces in more air for burning. But after driving the turbine the gases are still full of energy, and come out of the nozzle at high speed. This provides the propulsive thrust.

Ramjet. Air enters and is compressed by the motion of the ramjet through the air; energy is added to the air, by burning fuel, and the gases come out of the nozzle at high speed, providing propulsive thrust.

becomes. So by leaving off the propeller (and using a somewhat smaller turbine in consequence) one can get all one's thrust from the jet—this is the pure jet. Finally, as one goes even faster, the compressor too becomes unnecessary and can be left out. This is the ram-jet.

Engineers at Bristol Siddeley Engines Ltd have been working for many years to improve the burning process in jet engines and this research throws light equally on the burning process in ram-jet engines: hence it was logical for them to develop the ram-jet idea too. The ram-jet was fathered by the Royal Aircraft Establishment at Farnborough and the National Gas Turbine Establishment, and Bristol's are engaged in developing it into a more efficient form. (Work is also being done on a ram-jet test vehicle by D. Napier & Son of Luton.)

To get a flame to burn smoothly in a stream of air which is travelling at five or six times gale force is, of course, extremely difficult. Indeed it is difficult even to keep the flame alight: like a candle in a wind, it tends to be blown out of the back of the tube and to go out. The first thing that proved necessary was to provide a metal plate in the centre of the tube which would prevent this: it is called a flame stabilizer. But other problems arise. One is that the whole structure becomes extremely hot and, in fact, it is difficult to avoid the whole device melting. As one of Bristol's engineers explained: 'The problem is to contain a 2000° C. flame in a case which melts at 1500° C.' It was discovered that this difficulty could be met by bringing the relatively cool gases from the tail-end of the structure, which had finished their burning, and mingling them with the very hot gases which were just coming off from the burning process: the problem was to achieve this while at the same time achieving a smooth burning.

To find out just how the gases were circulating inside the engine, it was decided to make something which would reproduce the effect in a more visible form, and so a perspex model of the combustion chamber was made. This is simply a transparent tube shaped in the same way as the combustion chamber—but, instead of air and gas, water is forced through it. By placing small balls of polystyrene in the chamber, it is possible to see how the water swirls about and then to alter the various structures placed in the tube so that this swirling is controlled in the necessary manner. Smooth burning is best achieved

by a pattern in which, in actual combustion, the burning flame swirls back and lights the incoming mixture of fuel and air.

Inside the main tube is a secondary tube with holes in it: it is outside this secondary tube that the cooler gas passes, thus preventing the outer casing becoming too hot.

With the knowledge gained from this water analogue, real engines were built and fitted with baffles of various designs and tested on the ground to see what would happen, and to test the shapes developed in the water-model in practical conditions. In this way a body of knowledge about the effect of various small changes in design was built up. Where components are being tested, the apparatus for these ground tests is known as a test-rig, and, where complete engines are concerned, as a test-bench.

A test-rig or test-bench of this sort consists, in principle, of a large metal tube inside which a complete jet engine (or ram-jet) can be placed. A stream of air is fed in at one end and the exhaust gas is led away at the other. The jet engine's functioning can be observed through portholes and of course there are fuel controls, devices for igniting the flame, and so on.

It will be realized that a modern jet engine, such as the Olympus, produces a thrust of several tons in a forward direction and therefore—although it is allowed to move very slightly in order to measure the thrusts—it must be anchored very solidly when it is being tested on the ground; as a matter of fact the latest version of the Olympus engine produces 24,000 lbs. of thrust, which is more than ten tons and is about twice as powerful as any one of the engines used in the Comet. If one is standing with the door into the test-cell open the scream of air and gas is absolutely deafening. The level of sound falls markedly when the test-cell door is closed as a result of the silencing material used in the building. In addition the intake of the test-cell is silenced, and the exhaust is likewise muffled by being passed out through obtainers which look like giant clay pipes.

One of the currently interesting developments in jet-engine design is known as 're-heat'. As the term implies, this consists in injecting further fuel into the jet gases at the rear of the engine where it burns and so heats up the jet, to speed it up even further by giving it some more energy, for the air is usually not fully burnt when it leaves the exhaust tube.

Up to now the pilot either had to have the re-heat device on or off;

he could *not* bring it in gradually, rather as the driver of a racing-car must either use his supercharger or cut it out. Variable re-heat devices are now being developed. To make the task more difficult, there is more than one position at which the fuel is injected: in these test runs, it takes three or four men to watch the fuel supply to the various jets and to regulate the re-heat. Obviously in an aircraft, where there may be only a single man, the pilot, this is impracticable. What is wanted is a single throttle control which can be pushed forward and which can be made to regulate the various sections of the fuel-supply system, so as to give a smooth and progressive increase of power. Were the various factors allowed to get out of balance with one another, the temperature might rise to the point at which the compressor blades would melt.

Bristol Siddeley Engines Ltd are therefore working on evolving combined controls. To discover exactly how fast each valve should be moved in order to remain in step with the other valves calls for a good deal of experimental testing. This depends also on just how the burning process is going on in the engine, so that, after mechanical devices to link the controls have been worked out, they have to be tested on an actual engine. Clearly, these tests cannot be done in flight until they have been demonstrated on the ground to work reliably.

It was one of these test-runs of the Olympus engine intended to study the new control device which we decided to show in the programme in order that the public could see research on pure jets in progress.

A great deal of research has also been devoted to the compressor itself, which is a full-time study for many engineers. Here one of the main problems is to make the thing as light as possible. This raises the question of how finely cut the compressor blades can be made without introducing the danger of their breaking off and perhaps flying through the outer casing. If this happened the airstream would then rip the casing open and the engine would immediately be wrecked. When the engine is going at full speed the tips of the blades are travelling at over 1,000 feet a second and, of course, they are subject to great pressure from the airstream which they are slicing through and driving through the compressor.

Compressor blades are liable to break off if, instead of remaining rigid, they begin to vibrate. Every blade has a natural period of

vibration like a tuning fork, depending on its shape and the material of which it is made. Vibration gradually weakens the metal until a fracture occurs. Elaborate methods are therefore necessary to study blade-vibration in compressors while they are actually operating. This can be done by attaching to the base of one of the blades a small electrical strain-gauge which records the changing stresses in the blade and translates them into electrical signals. These signals can be led away through wires and finally taken out of the engine on slip-wings attached to the main shaft. They can then be fed into a cathode-ray oscilloscope and the various modes of vibration appear as different wave-forms on the cathode-ray tube. By running-up the engine it can be seen whether there are certain speeds at which the blade is particularly liable to vibrate, and if so, how much. Blade design can then be changed in an attempt to avoid this. In general, the object is to design blades so that their natural tendency to vibrate only occurs at speeds higher than the engine will actually run at.

Another aspect is that certain combinations of metal fuse together when they rub, while others simply wear. The blades clear the casing by a few thousandths of an inch, and if any distortion takes place, rubbing may occur. Obviously it is important that the blades, in this case, should simply wear down, and the combination of metals must be chosen accordingly. Consequently it is necessary to study the vibrations not only of blades of various shapes, but also made of various metals.

By research of this kind jet engines have been greatly improved in performance since the original design produced by Frank Whittle; their power output has been increased as much as twenty times and this power output is obtained for about half the specific fuel consumption. (By this I mean that *for a given amount of power* half the fuel is used. Of course, since the engines themselves are bigger, the total amount of fuel used has risen.) At the same time the weight of these engines has been increased by only about four times so that you get twenty times the power for only four times the weight. Since aircraft designers have to save every ounce of unnecessary weight, this is vitally important.

All the research work on combustion applies equally to the ram-jet. While the work on compressors has nothing to do with ram-jets, the ram-jet introduces new problems which have not been met so far with the turbo-jet, chiefly because the ram-jet flies above the

speed of sound. At these supersonic speeds 'shock waves' are produced and these are one of the great problems besetting design aeronautical engineers.

We had already explained something of this in our earlier programme from the wind-tunnels at RAE Wind Tunnels at Bedford. An aircraft flying below the speed of sound sends out sound vibrations in the air in every direction, including, of course, ahead of it; but when it begins to fly at the speed of sound it flies at the same speed as the noise which it is itself producing. So that the further noise which it produces builds up, as it were, on top of the existing noise. When it goes faster still the position is even more complicated, as it then overtakes its own sound, so to speak, and this is how the shock-wave problem arises. These shock-waves, in normal circumstances, run outwards and rearwards from the leading parts of the aircraft, forming a 'broad-arrow' pattern, the central bar of which is made by the plane.

A shock-wave is, in fact, a sudden change of air pressure from one level to another as one passes in the direction of movement, and the shock-wave will at any given speed remain in a particular position in relation to the plane. As the aircraft goes still faster the 'arrowhead' formation will generally become more acute, and as it goes slower will become more obtuse.

These shock-waves can be shown by a special kind of optical system called a 'Schlieren' system, which makes them look like broad, black lines. This can be used, for instance, to study the shock-waves created by rifle bullets. Equally it can be applied to engines which are being run on the ground. Much study goes into determining where the shock-waves will arise and altering the shaping of the engine so as to prevent them having damaging effects. Experiment shows that, at certain speeds, a severe buffeting is produced, as shock-waves shift and reform. This buffeting may be enough to wreck an aircraft if it is not controlled. At the same time, a shock-wave, since it causes a rise in pressure, can be used as a means of compressing the air going to the engine. Hence the intake of a supersonic engine is designed so that certain shock-waves are formed through which the air must pass on the way to the combustion chamber.

In a mechanical compressor, there is a trouble known as 'surging' which can develop under certain conditions. A supersonic intake

may be affected by a comparable phenomenon, which is called 'huzz'. It consists of a rapid oscillation of the shock-wave on the intake. As the engineers at Bristol were able to provide us with excellent film of these shock-waves 'buzzing', we were able to demonstrate this phenomenon on the programme.

In designing ram-jets the shape of the air intake at the front is extremely important because, as I have said, the intake is a simple tubular structure. In the circular mouth of the tube there is a very sharp-pointed spike which points forward. The edges of the ram-jet tube are sharpened to a knife-edge to minimize wind-resistance. At the Bristol plant, the engineers have tested a quarter-scale model of the intake in a wind-tunnel in order to discover where the shock-waves will come and what to do about them. As in the experiment already described, the tunnel consists of an arrangement for supplying a very fast airstream (from the same bank of compressors as before) with the addition of a Schlieren optical system by which the shock-waves which form can be projected on to a screen and studied.

As the ram-jet approaches the speed of sound, or, in the case of the model in the wind-tunnel, when the air is passing over and through the ram-jet at the speed of sound, shock-waves develop on either side of the mouth of the ram-jet. To be more precise there is a fan of shock-waves all the way round the intake, like the ruff round the neck of an Elizabethan: but, as the shock-waves are only seen in silhouette, what one sees is two black lines emerging on either side of the profile of the ram-jet.

As the speed increases still further these black lines move gradually backwards along the body of the ram-jet and a new shock-wave appears just in front of the point of the sharp spike. As the speed increases still further this shock-wave appears to bend over and surround the ram-jet in a cup-shaped way. What one cannot see in this model is that inside the ram-jet tube shock-waves are forming which fan inwards, if one can use the expression, from the inside of the tube. Experiments show that as the fuel-flow is increased—as is necessary as the speed increases—these shock-waves move forward and finally emerge from the mouth of the tube. It is at this point that the very violent fluctuation sets in which is known as 'buzzing'.

The Schlieren makes it possible to see just how the shock-waves are set up and collapse.

This forward movement of the shock-waves, therefore, sets a *limit*

to the amount which the pilot can open the trottle, and some means must be found to prevent this occurring. The Bristol engineers have established that this can be done by decreasing or increasing the size of the nozzle through which the gases pass after leaving the combustion chamber. The narrowing of the neck of this nozzle is intended to increase the speed at which the gases leave the tube—and hence the thrust—but by arranging for the size of the throat of this nozzle to be increased, as more fuel is supplied, the shock-waves can be retained in the best position in the tube. For practical purposes this control of the exit opening must of course be linked up with the throttle, so as to take place automatically at just the right moment and it is on this kind of problem (among others) that development work is now proceeding.

The supersonic bang of which we read so much in the papers is in fact caused by this shock-wave. Although in a wind-tunnel we see the change of pressure as a stationary thing, relative to the aircraft sound is continuing to travel at its usual 700 miles an hour and it is the arrival of this zone of sudden change of air pressure at the earth's surface which is responsible for the bang.

These are some of the tests on different aspects of jet and ram-jet functioning which go on at a place like Bristol Siddeley Engines Ltd. But they are not the whole story, for it is also necessary to test all these features together and, what is more, to test them in conditions which duplicate the low pressure found at various heights in the atmosphere up to about 100,000 feet. This is done in a fantastically elaborate test-plant, costing about £1 million—which is not expensive by present-day standards considering what the test-plant does. The heart of it is a test-cell, rather like those already described, capable of containing a full-size ram-jet engine. Into this is fed a stream of air from the compressors at speeds up to Mach 3·5—roughly 2,300 m.p.h. But it is necessary to reduce pressure in the test-cell, to simulate the effects of high altitude by sucking out the air and the exhaust gases from the engine until the pressure in the test-cell falls. Since air is being blown in at a rate of 160 cubic feet a second, which represents changing all the air in about four ordinary living-rooms every second, it will be realized that the amount of sucking which has to be done to reduce the air pressure is considerable.

This is achieved by accumulating enormous quantities of steam—forty-five tons of it—and suddenly releasing it through a series of

small jets in the bottom of a high tower. From the bottom of the tower a tube runs to the end of the test-cell through which the air and exhaust gases can pass. As the steam streaks upwards it creates a suction effect which carries the exhaust gases and air along with it. The principle is a common one and is used in some small-scale pumps, but here we find it on a prodigious scale. It takes four hours to accumulate the necessary steam, which is then released in about ten minutes. This rate of release represents the equivalent of about 70,000 h.p.

The air compression is achieved by Proteus compressors, the same as those found in the turbo-prop engines of the Britannia, but they are driven by electric motors. These total 26,000 h.p. and consume about 20,000 kilowatts of current—that is, as much as 20,000 1-bar electric fires, or enough for a small town.

Finally, the rear of the test-cell has to be cooled because of the intense heat developed by the flame shooting from the ram-jet; it has a temperature of perhaps 1,600° C. Spray rings are therefore fitted all round the tube and from them water squirts incessantly.

To regulate this elaborate equipment, a big control-room is needed with thick glass windows through which the test-cell can be seen. The test-cell itself only has thick temperature and pressure-resistant glass portholes on which the water from the cooling system runs down to cool them. As we go in to the control-room we see a number of panels. Those on the left-hand wall control the steam supply, the air supply and the air-conditioning system. Of the panels facing the test-cell, the first displays the controls for the cooling water, that in the centre the controls for the fine adjustment of the test conditions, while on the third are the throttles for the ram-jet fuel system.

It will be realized that it is not enough for this equipment just to blow a lot of air in and suck a lot of air out; the temperature and pressure of the air must be precisely measured, so that particular conditions can be simulated and the engineers need to know just what volume of air is being fed in. This call for a mass of instruments and dials.

Above the panels on the left-hand wall is a diagram showing all the main pipes and lines of the test-rig, together with their controlling valves. Illuminated signals show which valves are open and which valves are shut at any given moment.

In the centre, facing the test-cell, stands the engineer-in-charge,

wearing headphones and a throat-microphone. (This is a small microphone strapped round the neck so that it is held against the throat. It picks up the wearer's voice without picking up noises in the room where he is.) With this he can communicate with the various technicians outside the control-room—for instance, the men who control the compressors, or those who supervise the electronic recording-room. This is the place where many of the measurements are recorded. Something like a hundred measurements are made simultaneously during every test-run, and the readings of the various instruments are recorded in numerous rolls of paper by moving pens. These records tell how the pressure is changing at various points inside the ram-jet tube itself, thanks to signals which come from small measuring devices which have been attached to it at many points. At the same time changes in the rate of fuel consumption and in the thrust developed are also recorded.

On the right of the engineer-in-charge stands another man who controls the fuel supply by means of a number of levers which look rather like those in a modern railway signal-box. During each test the ramjet is 'flown' under conditions simulating various speeds and at various heights in order to discover how it performs and whether any particular combination of conditions is especially favourable or unfavourable.

The test-plant is protected by elaborate locking systems designed to prevent any risk of the steam being released or air being blown in, while anyone is in the test area. A safety lock must be operated to release the controls. The key must be taken from this lock before it is possible to open the door into the assembly bay, in which the test-cell is situated.

A lot of the work carried on in Bristol Siddeley's experimental establishment is what is known as 'development work'. It is directed to getting an engine or component to function reliably enough and efficiently enough for ordinary use. (In contrast, in research work the object is to discover the basic principles which govern the fundamental processes by which engines work, so that, in the light of this knowledge, better engines can be designed). Such work probably costs far more than the research which led to the original idea of the ram-jet. For example, to develop a ram-jet-powered aircraft may entail a cost of several million pounds.

Because of its lightness and efficiency at speeds of the order of three

times the speed of sound, the ram-jet is being seriously considered for use in both civil and military aircraft. The design of such aircraft, however, presents unusual problems for two reasons.

In the first place, as I have explained, a ram-jet engine cannot operate when the aircraft is standing still, which poses the question of how to take-off and land. At Bristol Siddeley Engines they are working on the idea of combining the ram-jet with an ordinary jet (turbo-jet) engine in order to lift the aircraft off the ground and bring it up to the speed at which the ram-jet can start operating, and also to provide power during the approach and landing. It would be costly in weight and materials to have two completely separate power-plants. Besides, this would make the aircraft unnecessarily bulky and so spoil its streamlining. In the Bristol Siddeley design the same air intakes can be used for both the jet and the ram-jet engines: this reduces the size of the intakes necessary, since at low speeds, when the turbo-jet needs a lot of air the ram-jet needs very little, and at high speeds the ram-jet needs a lot and the turbo-jet very little. But nevertheless the air intakes would be extremely large, perhaps the size of garage doors. A large part of the aircraft would consist of a large air duct feeding the engines, and thus about 75 per cent of the aircraft's lift would actually be created by the surfaces of the propulsive installation itself: so that the layout of the engine will directly affect the aerodynamic qualities of the aircraft.

These problems are much more serious when human beings are to be carried than when an unmanned missile is concerned, and especially so when fare-paying passengers are concerned, who expect to be maintained in conditions which are not merely tolerable but comfortable. In the nature of the design, the passengers must be much nearer the engine than they are in the case of the planes with which we are familiar. As they will also be near the huge air takes, noise reduction as well as cooling problems may arise.

On another page will be found an artist's impression of how such an aircraft might look: it was prepared for the broadcast by the Bristol Siddeley Engines' engineers and although it is, of course, simply an impression it can be regarded as a well-informed one. The development of such an aircraft is a matter of ten to fifteen years' work.

An aircraft which could fly at 2,000 miles an hour when it had attained its operating height would reach New York from London

in two hours. The unsolved problem is still what the economics of such an operation would be. There would not be any problem of exceptionally long runways, because of the large wing area inherent in the design, but the high first cost of such an aircraft will probably make such trips expensive unless there are sufficient passengers available to make possible operation round the clock.

Such an aircraft would move round the earth faster than a given point on the earth rotates, even at the Equator, so that it would, when travelling east to west, gradually retreat in time, landing well before it had taken off. The winter time-difference between London and New York is five hours, and so an aircraft leaving London at midday London time (which is 7 a.m. New York time) will arrive in New York at 9 a.m.—three hours before it started, if the passengers judge by the clocks which they see on arrival. If such an aircraft took off an hour after sunset it would see the sun come back again up the western sky and would land two hours before sunset.

10

The Friendly Enemy

How scientists are using radiation to kill bacteria and how they are persuading bacteria to help clean up our rivers.

ONE day in November 1958 I found myself standing twenty feet above the ground on the rim of a great concrete tank containing some 200 tons of specially-cultivated bacteria. These bacteria were eating up the poison in the effluent produced by one of the biggest coke-plants in the country. Behind me towered the huge mass of this six million pound National Coal Board installation, and pipes containing the effluent ran from the benzole tower and a dozen other sources to the tank on which I was standing.

In 1951 the Government ruled that all industrial concerns must clean up the liquids discharged from their works before pouring them into local rivers, for these poisonous effluents have in many areas destroyed all the fishing and created other havoc. The principal harmful item in the effluent of coke-plants is a group of substances called phenols, one of which is carbolic acid, formely much used as a disinfectant. This powerful chemical, and others like it, not only kill bacteria but may poison fish, etc. It is forbidden to have more than five parts of phenol in every million in river water—but many effluents contain more like a thousand parts per million.

At my feet bubbled and frothed tons of dark brown sludge which I knew to be composed of billions of bacteria, and a warm steam and a most peculiar smell arose from the tanks. At my side stood Mr E. R. Forlin and Mr D. E. Cunningworth, of the National Coal Board who have been responsible for developing the process and Mr E. C. Hill of the Bacteriology Department of University College, Cardiff.

Though carbolic acid, like other members of the phenol group,

kills most types of bacteria, yet there are some which can actually live upon it provided the amount is not too great. The idea therefore occurred to these scientists that such bacteria could perhaps be sorted out from among other bacteria and encouraged by a conditioning technique to attack the phenols in effluent.

To test this idea an experiment was first of all made on a small scale: a small area of earth was watered daily with dilute phenols. This had the effect of killing the bacteria which did not like phenol while encouraging those which did, by providing them with plenty of phenol to live on. After the earth had been in this way encouraged to provide a large population of these bacteria, a small quantity was removed to a flask and fed with a dilute solution of phenol while the conditions in which they could best destroy it were studied. It was found that the mixture must be kept well aerated by bubbling air through it and be kept warm. In fact the rate at which these bacteria functioned most efficiently was between 35–40° C. (96–104° F.) so that it pays to accustom the bacteria gradually to much higher temperatures.

What was wanted for industrial use was not a batch process, in which each tank would have to be replenished, but a continuous process in which the strong effluent could flow in one end and go through stages of purification until almost all the phenol had been removed. So in the laboratory two-and three-stage apparatus was constructed, in which the phenol could be attacked by two, and later three, gangs of bacteria in succession.

When this had been shown to work effectively the next step was to build a pilot plant. The National Coal Board, therefore, built an experimental unit at the Maritime Colliery, Pontypridd, containing some 1,500 gallons of sludge, and a suitable area of ground was watered with phenol to produce the population of bacteria to fill it.

At this stage a number of problems emerged. It had been found that results were improved by putting baffle-boards in the tanks, and at one point these were made of wood. But the wood attracted the kind of bacteria which break up wood and these contaminated the liquid in the tanks. At a later stage many of the phenol-consuming bacteria died and the sludge began to become inactive. On investigation, it was found that copper, in minute traces, was getting into the mixture because the bacteria were in contact with a copper diffuser at one point in their career. The copper poisoned the bacteria, so

plastic pipes had to be substituted for the copper. Even this may not be a final answer for there is now evidence that bacteria, which evolve rapidly because they breed so rapidly, are beginning to develop strains which can live by breaking up plastics. For similar reasons no zinc or galvanized metal must be used, nor must there be any bare steel or iron.

The bacterium which so conveniently breaks up phenol is called *Pseudomonas*. It exists in ordinary garden soil. This can be shown by putting a little of it in a test tube: if a dilute solution of carbolic acid is added to the soil after incubation it will be seen to go slightly milky. Carbolic acid is itself colourless and the milkiness indicates bacterial growth, due to their feeding on the carbolic acid.

This work has not completely solved the effluent problem, however, since the purified liquid still contains too much ammonia. However, there are also bacteria which oxidize ammonia to nitrates and Hill, Forlin and Cunningworth are working on developing a bacteriological method of dealing with the ammonia problem. Using similar methods Hill has in the laboratory induced different bacteria to remove about 250 parts per million of ammonia per day. Nutrients again have to be added and the success of the bacteria is tested by the amount of nitrates and nitrites produced. This is done by adding a reagent which becomes coloured in the presence of nitrites and measuring the change of colour in a device called an absorptiometer. A light shines through the liquid: the amount absorbed depends on how dark the liquid has become due to the formation of nitrates and nitrites. A photo-electric cell measures the amount of light transmitted.

This process holds out an even more interesting possibility, for if the ammonia could be converted inexpensively to nitrates we should have a fertilizer instead of a poison and so the process could be transformed from an expense to a positive source of income to the people using it.

The cost of the phenol purifying process is, at present, about fourpence (per ton of coal carbonized) as against several shillings a ton for purifying it chemically. There are today some ten plants in the world working on this principle, of which two are in India. There have been inquiries from Japan, the USA and other countries which are becoming very interested in the idea. Nor is the coke industry the only one to which it can be applied—many other

industries have effluents which might be treated in this kind of way very cheaply—in particular, the plastics industry. Laboratory experiments on the effluents of power-stations and oil refineries have already proved successful.

Bacteria are more familiar to us as the enemy of man than as his friend. It is bacteria which are responsible for the decay of foodstuffs and of all living matter once it has become dead and unable to resist bacterial infection. There are many different sorts of bacteria—probably millions of strains—some of them beneficial to man and some of them definitely dangerous like the bacteria which produce tetanus or 'lock-jaw' and which flourish in the soil.

Bacteria are, of course, extremely small and can only be seen under the microscope though they are not as small as those other agents of disease, the viruses.

The fact that there are hundreds of thousands of bacteria in the room in which you are sitting can easily be demonstrated by taking a glass dish, known as a Petri dish (from J. R. Petri, the German bacteriologist who designed it) which has been sterilized by baking it and on which has been spread a so-called culture medium—that is, a jelly on which bacteria thrive. As already mentioned in *The Thread of Life*, it is usual to use a jelly made from Japanese seaweed and known as 'agar'. In this jelly nutrient substances must be dissolved to act as food for the bacteria.

If such a dish of jelly is exposed for about fifteen minutes to the air, then covered with a lid and placed in an incubator so that the warmth will encourage the bacteria to subdivide, we shall see after about twenty-four hours a whole series of little spots on the jelly. These clumps are, in fact, colonies of bacteria, each of which has grown up by the division of a single bacterium which landed on the jelly during the quarter of an hour during which it was exposed. These bacteria can be picked off and placed on a microscope slide for inspection. The bacteria continue to multiply before our eyes and, when conditions are suitable, they will double in number every twenty minutes. So that in twenty-four hours, in favourable circumstances, a single bacterium could become twenty-eight billion bacteria. Usually a figure quite as high as this is not achieved because the bacteria finally get in one another's way and become separated from the nutrient medium, though if they are able to drift away in a liquid a high rate of multiplication can be maintained. It is this

astonishing power of the bacterium to multiply itself which makes control difficult. A single harmful bacterium getting into the bloodstream, if it escapes destruction by the various defence mechanisms of the body, can soon give rise to a sufficient number to make you seriously ill, or indeed to kill you.

Many bacteria are carried about by the ordinary bluebottle fly which is too often seen buzzing around the kitchens and in cafés. Such flies carry bacteria on their bodies and feet and this again can easily be proved by placing in a bottle some of the same culture medium as before, which has been kept sterile, and then placing a fly in the bottle for a few moments. After a few seconds the fly can be removed, the bottle plugged up and put into the incubator. Twenty-four hours later it will be seen to be covered with colonies of bacteria, much as the plate was, but very much more numerously. Some of these bacteria would not be harmful to man, they will be bacteria which make food decay and which turn milk sour, but among them may well be disease-causing organisms.

Consequently any methods of destroying bacteria are important to man: one of them is extreme heat—which is why we boil water before drinking it if we are uncertain whether it is infected. Extreme cold prevents bacteria from multiplying, which is why we place things in a refrigerator. We can pour destructive chemicals, such as carbolic acid, on them. But now a powerful new weapon has come into the hands of the scientist: short-wave radiation. In principle this has great advantages. It kills bacteria without causing any rise of temperature, so that foods can be treated without cooking them; then again, food can be packed in an airtight packet before irradiation, for the radiation will pass through most packaging substances. Thus there need be no risk of bacteria getting in after sterilization has taken place, a thing which has been the cause of at least one serious outbreak of food-poisoning.

Experiments are therefore going forward to see how well food will last after being irradiated. It is also necessary to see whether radiation produces any harmful effects and whether it damages the taste or consistency of the food in such a way as to make it less pleasant to eat. At Harwell, for example, potatoes have been found to be preserved satisfactorily after only a small dose of radiation and by the time that the unirradiated potatoes are deteriorating into a messy pulp or sprouting, the irradiated ones remain unchanged. The

Russians announced, at the last Geneva Conference on the peaceful uses of atomic energy, that they have cleared such irradiated potatoes for human consumption. The Americans are also carrying out large-scale feeding tests on human beings.

Grain also looks a likely subject for this treatment: a sterilizing dose may stop the breeding of beetles and weevils and prevent great wastage. Soft fruits may also be treated: radiation, it has been shown, will stop the growth of mould on plums, and experiments have also been conducted with strawberries.

A light dose of radiation will also knock down the bacteria to a very low level in bacon and sausages, which can be preserved for long periods in this way.

There is, however, certain evidence that the radiation causes substances within certain foods to break down into others which may affect the taste and possibly the purity. Research which has a bearing on this problem is being conducted at Cardiff University and the man in charge is Dr Glyn Phillips. Dr Phillips emphasized to me that he and his staff *do not* irradiate *food*. Theirs is a more fundamental study to discover what effects radiation has on carbohydrates, a class which includes sugars and starch, which are constituents of many foodstuffs. Their results are therefore of interest to others who study the effects of radiation on food. Cardiff University possesses a powerful radiation source composed of a piece of radioactive cobalt prepared at Harwell. This variant of normal cobalt is known as cobalt 60. I felt, therefore, it would be interesting to show how these powerful sources are handled and to go into the question of what the food tastes like afterwards and how research is done.

To visit the source one goes down to the cellar and through a big steel door, marked 'Radiation—Danger'. Beyond it lies a great mass of concrete within which there is a small room, perhaps five feet across in each direction, approached by a tunnel just wide enough to pass through. This is the radiation-room in which the material to be radiated is put. The radioactive cobalt 60 is withdrawn deep within the mass of concrete, and the tunnel leading into the room passes round the two corners so that no radioactivity can shine out of the room by it. Outside the block, separated from the radiation by eight feet of concrete, is the small control-room. The source itself, a very small metal tube perhaps 3 inches long and half an inch wide, can be wound out of the concrete by turning a handle. The tube in which it is

fragments (glyceraldehyde) or into a five-carbon (arabinose) and a one-carbon (formaldehyde). It also seems that the molecule can break down in other ways.

To discover what products have been produced after irradiation, the method known as 'paper chromatography' is used, as already described in Chapter 6.

Similar experiments must be done for other varieties of sugar, such as sucrose and dextran, and also for starch. No doubt it is these breakdown products which cause irradiated meat to have a somewhat acid taste and which cause strawberries somehow to lose their normal texture and to taste rather flat. Butter, too, acquires a very peculiar taste even at low levels of irradiation. Just how these changes tie up with the changes in specific substances has still to be investigated.

Another aspect of the work is to study what the resistance of different strains of bacteria is to radiation. It is known that different strains have different resistance and that the conditions during and after irradiation effect survival. So far the Cardiff group has studied about six varieties. The method is to contaminate the agar in two Petri dishes in the way I described earlier, one suspension having been irradiated while the other is used as a check or control. After twenty-four hours a count is made of the number of bacteria surviving, as indicated by the growth of visible colonies.

The fact that these breakdowns of sugars into substances like glyoxal and gluconic acid takes place freely only in water suggests that what happens is that the radiation reduces the liquid to its components or radicals and it is these which then react with the sugar and cause the molecule to split up. Something similar seems to occur when such liquids are irradiated with ultra-violet light.

It seems, then, because of this chemical breakdown of the food it may be some time before radiation replaces refrigeration and heat treatment as a means of sterilizing foods.

However, there is another application which may become practicable much sooner. Food is not the only thing that people want to sterilize. Another is many kinds of pharmaceutical drugs; those which have to be injected into the body, particularly, must be sterile—otherwise bacteria might be injected at the same time. Penicillin is a good example and you may be surprised to hear that about one-third of the total cost of manufacturing it is due to the elaborate precautions which the manufacturers have to take to see that the drug is really

completely sterile. The staff who prepare and pack the drug have to work in sterile rooms, the air in these rooms has to be elaborately filtered and sterilized, the staff themselves must wear white overalls and gloves, and gauzes over their face like surgeons, while elaborate precautions must be taken to prevent bacteria being brought in through the doors when people enter.

The price of such drugs could be greatly reduced if it were possible to make them in clean but not necessarily sterile conditions and then use radiation to sterilize the drugs after they had been packaged. Down at Cardiff they are experimenting on these lines, working particularly with penicillin. I talked to Mr Hill, who is working on, this, about the undertaking. His first problem was to find out how much radiation was necessary to kill bacteria in penicillin. To do this effectively it is necessary to make sure that the penicillin is contaminated to the same extent in each experiment. As Hill explained to me, what he does is to dissolve penicillin in sterile water in just the same way as the doctor does before using it for injection. This he contaminates with a measured amount of a suspension of bacteria in water, using a bacterium known as *Bacillus subtilis.* The contaminated solution of penicillin is freeze-dried (dried at low temperature) for a considerable period, and this causes it to return to the powder form. It is then put up in phials, ready for radiation. These phials are placed in the radiation-room. In order that they shall be exposed quite evenly to the radiation, they are placed on a turntable, which automatically revolves at a slow speed, so that each phial is exposed from every side to the source.

Every fifteen minutes the cobalt source is withdrawn into the safety tube, and one of the phials is removed. Consequently, at the end of the run, Hill has twelve phials which have been exposed for lengths of time varying by fifteen-minute intervals between a quarter of an hour and three hours.

Next comes measurement of the results. To discover the minimum amount of radiation which is necessary to kill all the bacteria, he starts by adding a substance (an enzyme) known as penicillinase. This has the effect of destroying all the penicillin present, thus leaving only the surviving bacteria to be measured, by the same method as previously described. In this way he can determine which dose would be just strong enough to be virtually 100 per cent lethal.

However, an interesting and unforeseen question has arisen in the

course of Hill's work. There is no doubt that the bacteria which have been sufficiently irradiated are incapable of multiplying. Since the method of examination only detects bacteria which are capable of multiplying, this follows automatically. And since it is only bacteria which multiply which are capable of causing decay and disease, this is what matters for immediate practical purposes. But Hill has recently come to the rather startling conclusion that, despite the fact that they do not multiply, many of them are not actually dead.

A living organism is one which carries on the basic bodily processes known as metabolism. Normally this involved absorbing oxygen, utilizing it in the body by the chemical processes which sustain life and provide energy for movement and other necessary functions, and subsequently releasing carbon dioxide as a waste product. (Some bacteria, it is true, can exist in the absence of oxygen, because they have found an alternative chemical process: for instance, they may derive their oxygen from the breakdown of sugars. But the principle is the same.) Any creature which carries on the process of metabolism must be regarded as living, by any normal definition of the word.

The gases absorbed and emitted by a metabolizing bacterium can be measured in what is called a 'Warburg apparatus' (named after the nineteenth-century German physiological chemist who devised it). Hill has found that if irradiated bacteria are placed in this equipment, they both 'breathe' and also adapt. That is to say, if he provides them with carbohydrates other than those which they normally consume, they will in little more than half an hour adapt to the situation and find a way of using them. For instance, most bacteria can break down glucose; but in its absence they will learn to make do with lactose (milk-sugar). To break up such carbohydrates they rely on substances, known as enzymes, which they contain. But enzymes are choosy, or as the biochemist says, specific: the enzyme which will break up glucose will not break up lactose, and vice versa. It seems, therefore, that the bacteria have some way of manufacturing the particular enzyme they need. Bacteria which do this are obviously *far from* dead.

This observation may have more then passing importance. It shows that the ability to multiply, and the ability to remain alive and functioning, are quite distinct, even in such simple organisms as bacteria. Now the difference between a cancerous cell and a normal one is that the former has lost the power to regulate its own growth

and rate of multiplication. If we could discover how it is in bacteria that the growth process can be switched off without damaging the normal life-processes of the cell, we might have a clue how to switch off the process of multiplication in cancer cells. Indeed, radiation is used to treat cancer tissue, but in such massive doses that it kills them completely. What is here envisaged is the possibility of finding a way of stopping multiplication *without* killing the cells.

Such observations bring us very near the question of what is life and what is death. That such fundamental questions should arise from a research which started out with a completely practical, down-to-earth purpose is very typical. For it often happens that 'applied' research leads back to problems of 'pure' research; while investigations with no practical aim whatever very often turn out to yield quite unforeseen practical applications.

11

The Voice of the Machine

An artificial voice helps scientists to study speech and to make telephone cables more efficient.

TELEPHONE engineers spend much time thinking how they can get more telephone conversations carried by a single cable. This is particularly important in the case of the long cables which cross the great oceans. One way in which this can be done is by treating each conversation rather as if it were a radio programme and sending it out tuned to a particular wavelength. At the other end of the wire, receiving sets select out from the mixture the particular conversation they want in much the same way as your radio set selects out from the ether the programme you want to listen to. This method, unfortunately, only works satisfactorily over fairly short distances and the longer the cable the fewer the number of conversations that can be sent.

Some years ago Walter Lawrence, working at the Ministry of Supply's Research Establishment at Christchurch, on the south coast of England, hit upon a completely new approach to the subject. His idea was that just as one can break up any colour into its components, i.e. the three primary colours, and represent it by a mixture of these, so also it might be possible to break up any particular sound uttered by the human voice into a number of basic components which, when put together again, would represent it. If this could be done and if the number of these components—or to use the technical word, parameters—were reasonably small, it might be possible to represent them electrically by much simpler signals than are necessary to convey all the complexities of the human voice.

So he started trying to break the voice down into its basic parameters. He decided there were six essential parameters:

the clicking noise which we use to indicate disapproval and which novelists usually write 'tchk, tchk, tchk'. More serious than this, because it occurs much more often in ordinary speech, it could not distinguish between 'sh' noises and 'ts' noises. For instance, if it wanted to say 'fish and chips' it was apt to come out like 'fis and tsips'. Of course one could often guess from the context what was being said and if, on the telephone, one heard that a man had had a meal of 'fits and ships' one would probably make the necessary adjustment and guess correctly what he had said.

When the signals from Lawrence's machine were sent along telephone cables they produced recognizable speech the other end but it was not quite good enough for one to recognize the voice of a friend, and some improvement was necessary.

Happily, a demonstration which he gave of this machine to the Acoustics Group of the Physical Society in April 1954, in London, was attended by some phoneticians—that is, people who study speech and pronunciation—from the Department of Phonetics at Edinburgh University. It occurred to them that this machine might help them in their own attempts to study speech. They, therefore, consulted with Lawrence and he, for his part, was interested because it seemed that they might be able to help him improve PAT's performance. So Lawrence and Mr David Abercrombie, the head of the Edinburgh University Phonetics Department, arranged a contract whereby James Anthony, the department's specialist in electronics constructed for them a replica of PAT to Dr Lawrence's specifications.

Here we had the makings of an interesting programme, for we could get the phoneticians to explain in some detail how speech is produced and studied and then we could show the parts of speech being put together by exhibiting PAT. Walter Lawrence and David Abercrombie readily agreed to co-operate and Lawrence kindly agreed to come to Edinburgh for the programme thus saving us from the less satisfactory alternative of filming him in Christchurch.

In Abercrombie's department Peter Ladefoged undertook to carry through the rather difficult and tiring series of speech demonstrations in front of the camera.

To demonstrate the fact that the loudness of speech depends upon the air pressure in the throat, Ladefoged had a rather spectacular demonstration. This involved swallowing a small rubber tube

ending in a very small balloon. But he did not swallow it through his mouth but up his nose and down the back of his nose into his throat, so as not to interfere with his speech production. Having got the end of the bubble into the oesophagus, or food passage, just below and behind the vocal chords, he connected the end of the rubber tube to a small cylinder with a plunger in it and by depressing the plunger inflated the balloon. The changes of pressure in the balloon which occurred when he spoke could be made to correspond to movements of a column of coloured liquid in a tube, rather like the older type of barometer, and he could make accurate measurements of the pressures developed by different words and sounds in this way.

In practice, however, Ladefoged finds it convenient to study these pressures on the screen of a cathode-ray oscillograph—the device I described in the opening chapter. In this case the beam was made to draw a horizontal line and the pressure signal coming in made the spot of light rise higher and higher according to how loud it was. So, as a particular sentence was said, we could see the spot of light climbing on the louder parts of the sentence and falling on the quieter parts.

The second way in which sounds differ is in pitch. To introduce this subject we made use of a rather spectacular demonstration which Ladefoged had arranged. This was a system of mirrors, one of which could be put right into his mouth so that one could look down his throat. The other mirrors were necessary in order to bring a beam of light into his mouth and turn it down his throat so that one could see what one was looking at. This was, in fact, his vocal chords. To show this we had to obtain a miniature television camera which could be fixed up to this system of mirrors, and Ladefoged had to bring his mouth over the small mirror and position himself so that the image of his vocal chords would fall upon the lens of the camera. This turned out to be pretty difficult and he rehearsed it a good many times before he could do it with a 50 per cent chance of success. On transmission he did not achieve it, in fact, quite as well as he did at final rehearsals. A further difficulty was that the mirror tended to mist up and had to be heated to prevent this. One could see Ladefoged's vocal chords open as he sounded a long *h* sound, but in speech, of course, the chords move much too fast to see with the naked eye. They can however be studied with ultra slow-motion cinematography.

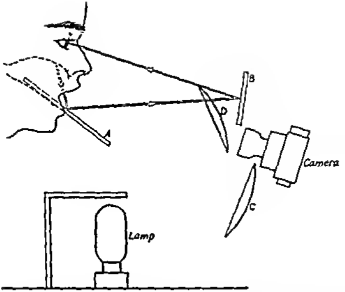


FIG. 7.—The Palatograph. With this apparatus a phonetician can study where his tongue has touched his palate, or can watch his vocal chords. He places his mouth over mirror *A*, which is fixed, and views his palate in mirror *B*, the position of which is adjustable. *Light from the lamp is reflected into his mouth and on to his palate by the concave mirrors* C and *D*.

Mrs Betty Uldall, another member of the department, had made a film of this by pointing a film-camera into a similar system of mirrors. This was not an ordinary film-camera but a very high-speed camera, taking some 5,000 pictures a second. These pictures were shown at the normal film rate of twenty-four a second so that the movements of the vocal chords were slowed up by some 200 times. The television screen was filled with a picture of these strange, waving curtains, the movements of which trembled and increased accord-cording to what the speaker was saying, and when the speaker began to laugh uproariously one could see them bellying about as if in some tremendous gale.

Ladefoged next showed how pitch is studied; this can be done

with another cathode-ray oscillograph in which the spot of litght rises higher upon the screen as the voice rises. He spoke the sentence 'It's a fine day today', first of all emphasizing the word 'fine' and then emphasizing the word 'day' and we could see the difference in the pitch pattern produced.

Next he went on to the fricatives, 'Hissing noises like "s" and "sh",' he said, 'are produced by putting the tongue very close to the roof of the mouth.' James Anthony had developed a very ingenious way of studying these tongue positions. Previously this had involved putting in the mouth a sort of dental plate or 'false palate' but this in itself somewhat changed the natural speech. Anthony's idea was to spray the roof of the mouth with a powder consisting of a mixture of cocoa and charcoal. For this demonstration, therefore, Ladefoged sprayed the mouth of another member of the department, Miss Lindsay Criper, with the powder and she then brought her mouth over another of these small heated mirrors. Into this we had a special camera pointed so that we could see that the top of her mouth had become completely black. Ladefoged then asked her to say 'tea' a couple of times and then put her mouth over the mirror again. We could now see that the tongue had wiped off the powder, all round the outer part of the palate while leaving it completely dark in the middle. If we had asked her to say another word, such as 'breathe' we should have found that the powder had been wiped off at the front and near the teeth, while other words would have wiped it off at the back of the palate and not at the front. This device is consequently called a palatograph. (See Fig. 7).

Finally, Ladefoged demonstrated the mouth resonances which make the difference between the vowels. These resonances can be demonstrated rather primitively simply by flicking the throat. As one alters the shape of one's vocal cavity the noise thus emitted changes. A rather more sophisticated version of this is to apply to the throat a machine designed to produce a buzzing noise. This is known as an artificial larynx and is made primarily for the benefit of people with damaged vocal chords; by making their throat—and thus the air in it—vibrate people can use their mouth and tongue to enunciate words which can then be clearly understood and thus it restores speech to them even if it is not very perfect speech. Ladefoged demonstrated this and a rather rasping monotone voice emerged, saying 'Eye on Research'.

A scientific device for studying these resonances accurately is the Sonagraph. This consists basically of a drum which rotates and to which a piece of special sensitive paper is attached. To study the make-up of overtones in a particular sentence one first records the sentence on the drum. Then the recording is played back over and over again. As it keeps repeating the recorded sentence, the Sonograph examines it in turn for all the frequencies at 50 cycles a second, all the frequencies at 100 cycles, all the frequencies at 150 cycles, and so on up the scale. Wherever it finds these frequencies it draws a line on the piece of paper for as long as they last. The net result is a diagram where we can see that the different vowels have produced different clusters of overtones.

When Ladefoged had finished these demonstrations, we returned to PAT, of which a glimpse had been given at the beginning of the programme, as it announced in its rather spectral tones 'Eye on Research, Eye on Research'. First Peter Strevens, who was the lecturer in charge of the synthetic speech research, made PAT demonstrate each of its parameters in turn. We heard the basic sound rise in pitch and change in loudness, we heard it make its hissing noises and modify its vowels. We then saw the belt on which wavy lines are drawn to regulate these six parameters so as to produce any given sentence. For the occasion of the broadcast Peter Strevens and James Anthony had managed to improve PAT's repertoire by solving the problem of enabling it to distinguish between 'sh' and 'ts'—for without this it would have been unable to say for us 'Eye on Research' but would have had to say either 'Eye on Researts' or 'Eye on Reshearch'.

By speeding up the rate at which the sentence is said while raising the pitch, and making a few modifications to the overtones, the chosen sentence can be repeated to sound like a woman or a child, and by adding extra hiss and keeping the basic sound going continuously it sounds like a drunk man, for that is what drunken speech consists of; the drunkard is too little in control of himself to switch off the sound production of his voice and switch it on again as demanded by the syllables he wants to say.

Lawrence has found that the controlling signals for PAT can be compressed into a telephone bandwidth of 150 cycles. To convey voice at ordinary telephone standards of quality requires about 4,000 cycles. Thus the work being done with PAT implies the possibility of

packing into a single channel some thirty times as many messages as at present. The Edinburgh phoneticians are inclined to think that about eight parameters will be necessary if it is to imitate speech perfectly; if the telephone authorities wish to transmit speech at this high standard they may have to reckon on rather more than 150 cycles and thus on a slightly smaller degree of improvement in the carrying capacity of the cable. But it may be that this not-quite-perfect speech will be good enough for practical purposes. The real problem is how much distortion can people put up with? Given a whole sentence one can usually guess a single doubtful word in it, but to test this question of recognition further Lawrence made use of the television programme itself. He induced PAT to say six words which it does not pronounce absolutely clearly and listeners were invited to send in on a postcard what they thought the words were. In point of fact the words chosen were as follows: Doughnut, Tightrope, Courthouse, Dockyard, Waxwork and Prize-fight. More than 9,000 viewers sent in postcards and of these a very high percentage correctly identified at least four out of the six words; the greatest difficulty seemed to be found in recognizing 'Prize-fight' and 'Courthouse'.

Actually PAT had enabled scientists to discover something about how language is understood which may prove relevant to the problem of clarity in telephone transmission. What he has discovered, in effect, is that we interpret a word in relation to the way in which the rest of the sentence is spoken. Hitherto many people have assumed that each word was interpreted and understood, so to speak, on its own merits.

To make this point clearer, let me describe the experiment. First of all, Ladefoged recorded the sentence as spoken by PAT in six different ways: 'please say what this word is.' The six versions of this sentence were produced by altering the values of the resonances present. Then he recorded the four words which we write BAT, BET, BIT and BUT. He replaced recordings of these words after the various recordings of the first part of the sentence in various combinations and then asked a number of people to say what the last word was.

It turned out that the answer which they gave depended very much on the particular type of resonances which had been used in the introductory sentence. (The sentence 'please say what this word is' was

In contrast with this, if one cannot feel the contacts of one's mouth parts, sounds like P, B, F, V, S, Z, TH, SH, and L become difficult to pronounce correctly. This can be shown by partly anaesthetizing the tongue, lips and the roof of the mouth.

It is rather more difficult to find a convenient experimental way of affecting proprioceptive feed-back (that is, the knowledge of the tension in our muscles) but this kind of feed-back must be important—since people can talk reasonably intelligently even when both their auditory and their tactile feed-back has been severely diminished.

Ladefoged demonstrated that a very strange effect is produced when the auditory feed-back is delayed. If a speaker hears his own voice delayed by about a quarter of a second he finds it very difficult to talk without hesitations and repetitions. This experiment is performed by recording the speaker's voice on a tape and picking it up with a reproducing head almost immediately afterwards and feeding it to headphones which he wears. I myself put these headphones on and tried the experiment. I found that I had great difficulty in saying my name and address. It was rather like trying to walk along a straight line when one was drunk; one made a mad dash to get through despite the forces which seemed to be pushing one off one's balance. Even such a simple thing as counting to ten becomes practically impossible.

What makes this particularly interesting is that the kind of speech produced is very like that of certain types of stammerers: this discovery has led to new research on the causes of stammering which may, it is now thought, be related, in some cases, to some kind of nervous delay in the feeding back of information about one's own speech. If any account of the programme has dwelt more on Ladefoged's contribution than on that of Strevens, Anthony and Abercrombie this is due simply to the fact that television must choose the most usual, and the writer, the most interesting aspects. Strevens and Anthony particularly went to great trouble in moving PAT to the building where the other demonstrations were carried out, and in Anthony's technical ability the whole programme depended.

Phonetics is a large subject and this programme only covered a very limited part of it. It includes, for example, such social aspects as comparing the accents of people in different parts of the country, and the *Edinburgh group works closely with the Linguistic Survey of*

Scotland, as well as working with the Medical Research Council Applied Psychology Research Unit at Cambridge. Another aspect of the subject is that of speech training and the elimination of speech defects, but there was no time to go into these aspects in a half-hour programme.

It is a curious thing that very few people are taking up phonetics as a life work and the department, which trains many arts students in phonetics simply as a part of their general course, would be delighted if some of them would take this subject up as a full-time scientific activity. As this account perhaps shows, there are many opportunities for new discoveries.

12

Breakthrough

Thanks to the brilliant technical advances which are enabling us to explore the fringes of interplanetary space, science is breaking through into new areas of knowledge.

'It was in the Naval Research Building Laboratory in Washington that I first saw a satellite,' Aubrey Singer told me. 'It lay there in the immense room, shimmering—because it was being vibrated 50,000 times a minute by test machinery to see if the delicate electronics in it would stand up to the treatment. I not only saw it, I actually touched it. Putting my finger on one of the aerial rods projecting from it, I drew it back and it sprang back into place with an audible twang.'

The reason Singer was there was because on October 4th the Russians had launched their first Sputnik. At the time he was planning the new *Eye on Research* series and the thought struck home that sooner or later *Eye on Research* must make a big attempt to present the achievements in this field for viewers. The firing of that first satellite was a tremendous event in world history and technologically a breakthrough of the first order. The event merited a programme of unusual magnitude to celebrate it, and so he had decided to build a programme of an hour's duration in which we would attempt to show what both Russia and America, as well as Britain, were doing.

A year earlier we had done a programme of similar magnitude on the launching of the International Geophysical Year. Prince Philip had been the commentator for this attempt to record a unique piece of international scientific co-operation. More than sixty nations had joined together to plumb the mysteries of the earth's crust, the seas, and the atmosphere above the surface. We had sent

cameras to every quarter of the globe. When scientific research has become a global undertaking, TV coverage must become global too.

It was on the basis of thoughts like these that Singer asked permission to go to Moscow and to the United States to prepare this programme, to Japan, to India, to the lip of Mount Vesuvius, to the top of the Pic du Midi, to Alaska, and to many other points. Big subjects require coverage in a big way.

The Rocket Propulsion Establishment at Westcott, is the Ministry of Supply establishment where high-altitude research rockets are built and tested. The RPE does research and development on both solid and liquid-fuel rockets.

Each type has its advantages. Broadly speaking, when the thrust is required for a period of less than half a minute or so, the solid-fuel rocket will be the best choice. There are many cases where the thrust is required for a period of a few seconds only. But for applications like the lifting of a satellite into space, where a large thrust must be developed for o period of two minutes or more, the liquid-fuel rocket is preferable. The solid-fuel rocket—a grown-up brother of the rocket which we let off on Guy Fawkes' Day, has no moving parts and is therefore lighter and has less to go wrong. On the other hand, it is much more difficult to vary the amount of thrust at different stages of the run. A certaio amount can be done by varying the way the fuel is packed into tbe casing, and by making various kinds of slots in it, but of course the rate at which energy is developed cannot be altered during the course of a run in the way that is possible with a liquid-fuel rocket.

To sum up, at the present stage of development, a liquid-fuel rocket has a much greater range than a solid-fuel one, but for short runs, a solid-fuel rocket is competitive.

Liquid fuels consist of at least two distinct substances. For to make something burn, you need (a) something combustible and (b) some oxygen to support combustion. Just as your fire will not burn unless it has a stream of air (which contains oxygen) so also with any kind of engine. But whereas jet engines, like car engines or steam locomotives, derive their oxygen from the air, the rocket takes its oxygen with it. This is why it can continue to work in interplanetary space, where there is no air to support normal combustion. In the case of liquid-fuel rockets, the oxygen is usually derived from

hydrogen peroxide (each molecule of which consists of two atoms of oxygen and two of hydrogen). This is the same substance which, in a very dilute form, is used by some people in order to bleach their hair.

Normally, the two propellants are stored in separate tanks and only come into contact when the firing key is depressed: combustion then takes place spontaneously. (In a few cases, however, substances which do not ignite spontaneously are used. These can be mixed in advance, and kept in a single tank, which saves weight and simplifies design. Such fuels are not the most powerful, unfortunately.)

. Typical propellant combinations are liquid oxygen and kerosene. A more powerful combination is liquid oxygen and liquid hydrogen. Still more powerful would be liquid fluorine and hydrogen, but fluorine is fantastically corrosive, and the problems of pumping it have not yet been solved, though the Americans are now building a motor intended to run on this combination.

A feature of the liquid propellent rocket is that either the fuel must be stored under pressure (so that it will pass into the combustion chamber automatically) or it must be pumped. In the former case, strong, and therefore heavy, tanks are required, the weight of which detracts from the rocket's performance. In the latter case, the fuel pumps must be driven by a turbine, itself operated by a stream of hot ejected gases.

The liquid-fuel rocket has one technical advantage which is worth noting. The limit of combustion temperature is set by the melting-point of the walls of the combustion chamber. If these walls are made double, and the unburnt fuel or oxidant is passed between them before it passes to the burning nozzles, it cools them. In this way, flame temperatures about 1,000° C. higher than would otherwise be possible can be permitted, and the operating time can be made longer.

The nature of the problem can be understood when it is realized that the temperature of the burning fuel may be about 3,000° C., which is about three times as high as the melting-point of steel. The real problem in designing rocket motors is to ensure that combustion takes place smoothly, and under control—for a sudden rise in temperature, even if only at one particular spot, could melt the casing, and when a rocket motor fails in this way, the results are spectacular. It is very different from what happens when a car seizes

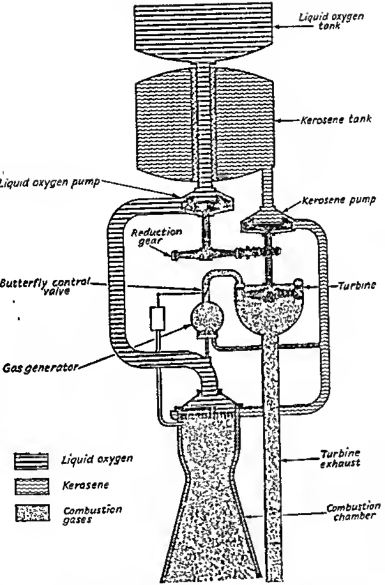


FIG. 3.—A Liquid Rocket Motor. The general lay-out of a typical liquid rocket-motor is shown here. Fuel is pumped into the forward end of the combustion chamber and oxidant into the after end.

up. As Dunning said to me: 'In rocket work, the margin between successful operation and catastrophic failure is very small."

To return to my story, however. As Singer got into the car, Patrick Dunning, the Director of the Establishment, suggested that they should go and see a liquid-propellant-motor firing, first, and later a solid-propellent-motor firing also.

As they approached the test-site, Singer noticed that the grass was scorched for something like 400 yards around, where the intense heat of the rocket exhaust had seared it. Near the firing-point was an old Churchill tank. This was used as a ready-made observation emplacement. Inside the tank sat an observer whose job was to report on the flame characteristics of the rocket during the firing. This was a safety precaution which enabled him to order an immediate shut-off of the motor, should the firing not go according to plan. Dunning invited him to stand on the top of this tank to watch the firing.

As he stood waiting, he saw steam beginning to spurt out of the back of the plant. It may seem odd that steam should come from a rocket-test. The explanation is that the intense coldness of the liquid oxygen, as it escapes from the vents in the rocket, chills the water vapour in the air and causes it to condense into fine droplets. It is a steam produced, paradoxically as it may seem, by cold not by heat.

Below the firing-stand, protected by concrete, was the control-room where equipment for recording, electrically, the behaviour of the motor is contained. In it there is also a periscope on which the behaviour of the engine can be watched at very close range, without risk. There are also special safety devices which shut down the rocket, should a mishap occur, such as a broken pipe or an electrical fault.

Below the motor itself is a steel slab, which deflects the flame, which the rocket emits, down a long tunnel. It appears to emerge for at least fifty yards. Such is the heat of this flame, that thousands of gallons of water have to be poured every minute over the steel base of the firing-tower, to prevent it melting. As the rocket fires, much of this water turns to steam, which billows out in dramatic white clouds.

Some people imagine that rocket motors work by discharging a blast of gas which presses against the air, much as the oar of a boat presses against the water. This is not so.

The burning fuel creates great volumes of gas which attempt to

expand, pressing in all directions against the sides and end of the combustion chamber. Since there is no rear wall, but only a nozzle, they can exert virtually no pressure towards the rear. The pressure sideways, at any given point, is exactly balanced by a pressure in the opposite direction on the opposite side of the combustion chamber: hence no movement sideways in any direction is imparted. But the position is different with regard to the forward and backward directions. Since there is no rear wall to the chamber, but only a nozzle opening to the exterior, virtually no pressure is exerted rearward, to counterbalance the pressure exerted forward. As a result, the chamber tends to move forward.

In calculating how fast it will move forward, we make use of the principle already mentioned when discussing the ram-jet, that action and reaction are equal and opposite. In a vacuum, the speed times the mass of the rocket must be equal to the speed times the mass of the ejected gases.*

Consequently, to achieve a good forward speed for the rocket it is necessary to throw out as much gas as possible and to throw it as fast as possible. Because of this principle rockets can work in outer space where there is no air—in fact they work better there, because there is then no resistance to the forward motion of the rocket nor to the gas being ejected behind.

One of the solid-fuel rocket motors, which the Ministry of Supply staff is testing at Westcott is called 'The Raven' and it was this which we were able to show in *Breakthrough*. An electrical primer is imbedded in the fuel, and this is ignited from a safe distance by an electric current. It is the Raven motor which powers the 'Skylark' high-altitude research rocket used at Woomera. (Rocket men make a distinction between the rocket motor itself and the rest of the rocket, which they call the vehicle—though the motor constitutes much the greatest part of the whole rocket.)

For televising the firing of the Raven motor during the programme we used a special reinforced control-point about fifty yards from the actual point of firing. The main television camera was about the same distance away, with the cameramen protected against possible

* The scientist speaks of mass, not weight. The *weight* of an object varies according to its position in the gravitational field. Thus a given piece of metal will weigh less on a mountain top than at sea-level, and very much less on, say, the surface of the moon. But its *mass* remains unchanged.

promises of co-operation in a programme of the achievements of the IGY should we decide to do one, but it soon became obvious that the Russians had no intention of releasing new material on rockets or satellites. To make matters worse, most of their old material had been sold to commercial film companies and there was only one film which they were prepared to let him have, that of the dog Laika.

He realized that his only chance was to see the head of the Academy of Sciences or, failing that, his deputy. On his tenth day in Moscow he finally managed to get an interview with the deputy, Academician Bardin. He explained what he had come for. Bardin replied, 'Mr Singer, you must return to London and write me a letter.' Singer returned to London, but actually sent him the letter from Moscow before doing so, and had it translated into Russian. No reply was ever received.

In America things were very different. The air was full of plans. Singer met Ray Johnson, head of the Advanced Research Projects Agency. It was from him that he learnt something of the comprehensive plans the Americans were developing. These included a communications satellite which would relay messages back to the earth and thus solve the problem created by the earth's curvature which makes it impossible to send short-wave messages over great distances. He also learned about the plans for the Atlas satellite which would raise a load of 3,000 lbs. into orbit. This was fired only five months later, in December 1958. It was on January 31st, 1958, that the Americans succeeded in putting their first satellite, Explorer I, into orbit. This was achieved by the US Army at Cape Canaveral. He learnt of the weather satellite designed to make a continuous survey of the earth's cloud cover and which, in fact, was fired in February 1959. When Johnson told him this he thought that he was telling him of something still some years in the future.

Johnson told him of their plans for sending up lunar probes—that is, rockets which would explore the neighbourhood of the moon. The first near-miss, under this programme, occurred in August 1958. It was this firing which explained why Singer, his colleague Philip Daly, and Raymond Baxter the commentator, had a rendezvous at Jodrell Bank Radio Telescope at six o'clock in the morning on October 11th. Professor Lovell had agreed to put the great radio telescope at Jodrell Bank at the service of the Americans to act as one

of the three tracking stations for this shot. The other two were in Hawaii and Singapore, respectively.

Outside the maio control-room at Jodrell Bank the BBC teams could see a little caravan, which was the American headquarters; from this caravan telephone links ran to Cape Canaveral, Los Angeles, Hawaii and Singapore. Los Angeles was the computing centre for the operatioo. On this day nobody was allowed inside the caravan.

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Jodrell and the tracking stations in Hawaii and Singapore were not, of course, the only places observing the satellite's path. Some of the best observations were made in this country at Farnborough: their readings were the most accurate of any in the world.

The reason for all this to-do was the fact that much can be learned about the upper atmosphere, and even the gravitational field of the earth, simply by observing accurately the satellite's path. It was from such observations that it was deduced that the earth bulges some 300 feet more at the equator than had beeo realized. Later observations also showed that the earth is not only like an orange, but also like a pear, in the sense that the northern hemisphere is rather slimmer than the southern one.

Inferences of this kind can be made because the path of the satellite and its height above the earth at a given moment are affected by the strength of the earth's gravitational field at the point immediately below it. And this field is stronger where the earth bulges, and weaker where it is does the reverse.

The major source of informatioo from satellites—and from high-altitude rockets too, for that matter—is the instruments which they carry aloft, the readings of which are radio'd back to earth. Up to now, such instrumeots have consisted chiefly of magnetometers designed to measure the magnetic conditions outside the rocket; ion-counters, to measure how far the sun's radiation is ionizing the atmosphere (i.e. splitting up its molecules into electrically-charged fragments); and instrumeots for measuring micrometeorites. Micro-meteorites are small fragmeots of rock, known to be flying about in space—for if large fragments arrive, as we know they do, there must certainly be many more small ones. It has beeo

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feared that this interplanetary dust may act as an abrasive, slowly wearing away the skin of an interplanetary vessel. Rockets are therefore often equipped with a grid of fine wires, carrying an electric current. The intention is that, if micro-meteorites are present, they will gradually break or wear away these wires, interrupting the current. This fact can be signalled back to earth, indicating how numerous they are.

The information from a considerable number of different instruments can be conveyed back to earth on a single radio channel, by means of a system known as multiplexing. A small motor drives a rotating switch, which samples the output of each of the instruments (the output always being electrical) about 5,000 times a minute. The number of instruments that can be conveyed in this way depends upon how rapidly the quantities being measured are changing; about twenty-four is usual, but for quantities that only change slowly and for which fewer 'samples' are required, the number can be about fifty. The combined output is radiated. Once received on earth, it can be split up again, and fed to oscilloscopes, so that the readings from each instrument appear separately. This enables the scientists to get an immediate visual impression of what the conditions are. For more detailed study, the twenty-four readings (or whatever the number is) are displayed side by side on oscilloscopes, and the changing pattern is filmed. From a study of this film, the scientists can observe the way in which the various factors being investigated are related to one another.

The great problem which the instrumentation experts are trying to solve is to provide enough electric current to run the motor, transmitter, instruments, and transponder in a satellite. The batteries which the Russians put in their first Sputnik lasted about three weeks, and probably constituted the greater part of the weight borne aloft. It can be estimated that about 100 lbs. of batteries would be needed. After these three weeks, no further information could be obtained from the instruments.

Scientists are therefore working on a means of making electricity from sunlight, by a system of photo-electric cells, so that such instruments could be powered indefinitely. Of course, this system would not work during the time the satellite was passing through the shadow of the earth. Since the state of the atmosphere in the shadow is certainly quite different from that in the sun, this deprives us of half the information, and of what can be learned by comparing the

two sorts of data. The next step is therefore a battery which can be recharged during the illuminated part of the orbit, with switches to bring it into operation during the other. However, we must also allow for the fact that the satellite may be rotating as it orbits, so that the light-cells must be placed on every side, and only a proportion of them will be functinning at any given moment.

Some progress is being made in this direction—the American 'paddle-wheel' satellite fired in August 1959 carried equipment of this kind. What remains uncertain is how long it will take the micrometeorites to wear away the surface of the photo-electric cells.

Up to the time of the performance of the *Breakthrough* programme in November 1958 there had been three Russian and five American satellites placed in orbit. Each of these firings had added at least one new fact to the stock of information about the earth. Sputnik I, although it carried no instruments, and nothing but a radio transmitter, nevertheless revealed that the density of the air at 100 miles above the surface is about four times what had been expected. Sputnik II revealed that the earth bulges at the Equator about 100 yards more than we thought it did. Sputnik III had nine instruments in it, and one of its more important measurements was a direct reading of the pressure of the atmosphere at a height of 500 miles. Though this was only one ten million millionth of the pressure at ground level, this was considerably higher than had been expected.

The most important information obtained from the American satellites was of the existence of a number of belts of high radiation outside the earth's atmosphere. These belts have become known as the Van Allen belts after the man who designed the instrumentation of the satellite and who made the calculations from the data it supplied. The radiation was so intense that it completely swamped the counters in the first satellite: there was some argument at first whether the instruments had been swamped or whether they were faulty, but more carefully protected instruments in the second satellite revealed that these radiation belts did indeed exist. It is believed that these belts of radiatinn are caused by protons, coming from the sun, being seized by the earth's magnetic field and concentrated in certain areas, particularly over the Equator. These belts of radiation are probably one of the causes of the aurorae seen in the polar regions; they offer a hazard to space travellers and some additional shielding of space ships may be called for.

In *Breakthrough*, we did not try to go into the details of satellite instrumentation, on which little work has been done in this country. We did, however, attempt to show something of the instrumentation of high-altitude rockets, which is well developed. For this purpose we took our cameras to the Royal Aircraft Establishment's testing-range at Larkhill, in the middle of Salisbury Plain, where these instruments are tried out, by an arrangement with the War Office. This is preparatory work for the actual firing of rockets at the bigger ranges at Aberporth and Woomera. Here the officer-in-charge, Mr Blanchard, explained the lay-out.

In the control-room at Larkhill the dominating feature was a tremendous desk covered with flashing lights and buttons; this communicated all the measuring equipment dotted about the firing range. There were high-speed cameras, radar equipment for following the rocket and kinetheodolite posts. (A kinetheodolite is a kind of telescope equipped with a film camera with which the flight of the rocket can be followed and recorded.) There was also equipment for receiving short-wave signals from the rocket (telemetry).

But information can be obtained from rockets also by simpler methods. We included in the programme two examples of the types of experiments which are being carried out by the Ministry of Supply, in collaboration with the Royal Society, with the Skylark rockets. The rockets are able to carry scientific equipment to altitudes of 100 miles or more.

The sections containing the instruments are placed in front of the rocket motor and its stabilizing fins. A nose-cone completes the construction. One of the sections shown contained eighteen tubes from which grenades could be ejected by a timing mechanism. Once clear of the rocket, the grenades detonate in turn, producing both a very bright flash and a very loud bang. Special cameras, whose plates are kept permanently exposed during the testing, photograph the flashes which appear as a series of pinpoints of light. These enable the precise position in space of the rocket at the moment of detonation to be determined. At the same time the time of arrival of the sound-waves from the explosion is recorded at a number of ground stations: of course this is some seconds after the flash. In this way the speed of the sound-waves at the different heights of the rocket can be deduced. Since the speed depends upon the pressure and temperature of the atmosphere, information can be gathered about how this tempera-

ture and pressure alter at the different heights. The calculations involved are carried out by the Department of Physics of University College, London. Such calculations also yield information about any winds which may be blowing in the upper atmosphere.

For the programme these grenades were ejected from a stationary rocket, and although the transmission was at night, the huge curve described by each grenade as it was ejected could be distinctly seen in the arc lights.

The second kind of upper atmosphere experiment shown is more difficult to explain. It concerns the ionosphere: this is a portion of the earth's atmosphere in which there are charged particles—electrons and ions. There is a belt of these particles stretching right round the globe, caused by radiation from the sun impinging on the outer atmosphere. These charged particles affect the behaviour of radio-waves, and until recently the ionosphere could only be studied by observing how radio-waves change their direction of travel when they encounter the ionosphere. Now, rockets such as Skylark enable scientists to fly instruments through the ionosphere. Thus they can make direct measurements of the distribution of these charged particles.

In Skylark, equipment devised by the University of Birmingham is placed in the nose-cone to carry out such measurements. It consists, basically, of an electronic oscillator. The frequency of oscillation is determined by the electrical capacity which exists between two portions of the rocket, these two portions being carefully insulated from one another by a fibre-glass ring.

One can demonstrate that this is so by placing one's hand between the two portions of the rocket: if the oscillator output is fed to an oscilloscope, the waveform can be seen to change when this is done. When the rocket is in flight, the capacity effect changes according to the number of charged particles in the ionosphere passing through the gap between the two parts of the rocket; and so, from the signals which the oscillator sends back to earth by a short-wave radio link, it is possible to deduce how the density of the zone of charged particles is changing with altitude.

The smaller and lighter the apparatus for a given experiment can be made, the greater is the altitude to which it can be carried by a given rocket. Alternatively, with lighter apparatus a given rocket can carry more kinds of equipment, and thus can carry out more ex-

periments in a single firing. Much work is being put into miniaturizing the equipment.

A further problem in certain experiments is that the measuring equipment must be fully exposed to the rarefied atmosphere at high altitude. At the same time it cannot be flown up through the dense part of the atmosphere in an exposed condition or it would be damaged. Hence provision must be made to strip off the protective nose-cone when the rarified region is reached. This is done automatically by a clockwork mechanism.

A problem with which *Breakthrough* did not attempt to deal is that of controlling the flight of rockets and missiles, it is however, one of the most interesting features. I mentioned earlier that these rockets contain automatic control systems, resembling the automatic pilots used in aircraft and ships, to keep them on a predetermined course. Such devices are, however, far from perfect. Gyroscopes do not maintain their orientation in space quite exactly, owing to the effects of friction at their bearings. The error may amount to as much as one degree at the end of five or six minutes, which is about the burning time of a satellite rocket system. This is enough to make quite a difference in a flight of several thousand miles.

It is also quite tricky ensuring that the controls do not overcorrect the rocket's deviations from course. If this occurs, the rocket will 'hunt', or veer from side to side. Or rather, since the rocket must be controlled both in the sense of yawing from side to side and of pitching in a vertical plane, and since hunting may occur in both these movements, the cumulative effect may be a movement known as 'precession', in which the nose of the rocket describes a circle, and the tail a contrary circle, while the rocket pivots about its centre of gravity. Such movements waste energy and do not make for accurate flight.

But the problems of keeping the rocket on a straight-line course are only the beginning of the story. The rocket system which puts a satellite into orbit has to carry out a flight-plan which typically consists of five distinct phases. (1) The rocket rises vertically through the densest part of the atmosphere. (2) The rocket gradually tilts over until it is flying at a much shallower angle. (3) After the second-stage motor has dropped away, the rocket coasts on through the almost non-existent atmosphere until at the orbit height. (4) The last stage is

fired, and boosts the nose-cone to a sufficient speed to enable it to remain in orbit (about 18,000 m.p.h.). (5) The satellite itself is ejected from the rocket, and the nose-cone falls away.

Any one of these phases can go amiss, and frequently one does.

In firing a military missile, instead of a satellite, stage (4) would comprise the tilting of the missile into a downward path at the correct point, and stage (5) would be the slowing down of the missile, so that it should not re-enter the atmosphere at a speed which would cause it to become white hot and burn up.

It is possible to build into the rocket's automatic pilot a programme which will carry out these phases automatically. The disadvantage of this is, if the flight does not go according to plan, it is impossible to make any attempt to correct the error. With ground control, if the second stage should burn out earlier than planned (let us say) it might be possible to allow a longer coasting period, for instance. On the other hand, ground control is not highly reliable. Electronic equipment is apt to fail, and especially when subjected to the very high accelerations of rocket flight. Often, it works perfectly on every test, only to fail when the actual flight takes place.

When ground control is used, one cannot normally rely on radar to indicate the position of the rocket, for the echo thrown back by such a small, remote object is too weak to be received, except by a large radio telescope. Consequently, it is necessary to build into the rocket a device known as a transponder. This is, in effect, a simple radio receiver and transmitter, so arranged that any incoming signal is immediately re-transmitted. It is this transmitted signal which is picked up by the ground radar. Here too is something which can easily go wrong.

The next step after putting a satellite into orbit is certainly the attempt to send up manned vehicles. The existing tiny satellites will be replaced by 'space stations' whirling ceaselessly round the earth: the military uses of such stations, with their power of observing the surface of every part of the planet, ensures that they will be constructed, apart from their scientific value. But before this is achieved man will probably have circled the moon and returned to earth. He may even have landed upon the moon.

The approach of such possibilities has created the new scientific field of 'space medicine'—the study of how man can stand up to the exceptional conditions of space flight. He will have to endure intense

gravitational fields due to acceleration at take-off. While orbiting or falling he will, on the other hand, be weightless. He will have to pass through belts of powerful radiation; when his vehicle re-enters the atmosphere he may have to endure, temporarily, intense heat. On top of all this there will be the psychological perils: the strange states of mind induced by isolation and remoteness.

Russia and America are busy in studying such problems. Britain, however, has no space-medicine programme, the RAF maintains however, Farnborough, an Institution of Aviation Medicine, where the problems of high-altitude and high-speed flight are studied. These problems are similar to many of the problems of space travel.

This work is little known to the British public, which hears too exclusively of American work, and we were determined to fight our way through the security regulations and to show something of it in *Breakthrough*.

The pilot of an aircraft, when making a tight turn, or when pulling out of a dive, is subject to severe gravitational stresses, similar to those which the crew of a rocket might experience at take-off. To study such stresses the Air Ministry has built, at Farnborough, a vast centrifuge—a whirling arm, some sixty feet long, carrying at each end a cage, in which a human being can lie or sit.

It was Philip Daly, the producer, who had done most of the filming for the Geophysical Year programme, who was in charge of filming these sequences, and in what follows I shall be telling you what he told me.

The doctor-in-charge took Daly into the vast circular room containing the arm. It reminded him of nothing so much as a television studio. Across one side (if a circular enclosure can be said to have a side) ran a gallery, shut off by double glass walls; from here, the whole operation was controlled. But in addition, for greater safety, the doctor-in-charge of the experiment sat in the very centre of the pivot of the whirling arm. As he rotated with the arm he could observe the reactions of the person undergoing the experiment.

As the arm began to swing round, the cage or cab in which this man sat, began to swing out, like the seats on a fun-fair 'chairoplane'. As the arm reached the intended speed—about one revolution every two and a half seconds—the cab had swung out through almost ninety degrees, so that its occupant's head pointed towards the centre of the circle, and its base almost brushed the walls. The

wind produced by this movement was terrific. A force of five 'g' was now being exerted on the occupant, and the forward speed of the cab was about 40 m.p.h. though it looked much faster.

It was clear to Daly that he could never get cameras and lights into positions to photograph the arm whirling at full speed. He therefore decided to place an automatic camera actually on the arm, photographing the man in the chair as he underwent this gruelling experience. At the same time he arranged to put a microphone and tape-recorder on the arm, so that he could describe his experiences.

With this machine, stresses of thirty g, or thirty times the normal force of gravity, can be simulated, the cab travelling at 115 m.p.h. Because the radius of the arm is short (about thirty feet) the stresses are equivalent to those exerted on an aircraft at much greater speeds on vastly greater rates of turn. No one could survive such a stress, however, for more than a few tenths of a second. Pilots pulling out of dives have survived stresses of eight g for brief intervals—the greater the stress the shorter the time the body can tolerate it. Such stresses hurl the blood into the feet, draining the brain and producing brief unconsciousness, or 'black-out'. Even at five g vision may temporarily vanish. However, it has been calculated that a rocket crew need not undergo more than 3 g acceleration at take-off. The question is what controls they could successfully operate in such conditions, and which is the best position to withstand the stress.

The immediate question, however, was whether our camera and recorder would continue to function at 5 g—for this was the maximum speed at which the Air Ministry would allow the BBC apparatus to be run. In particular, there was a danger that the recorder would be thrown out of synchronism with the camera, so that words would no longer coincide with lip-movements. A test-run, followed by some complicated calculations, showed the tape had run for a time appropriate to the film consumed, so we concluded that all was well. When the film was developed, this proved to be the case.

All was then ready for the actual run. The voice of the controller in the gallery came over the loud-speaker, addressing the doctor-in-charge, 'Are you ready, Peter? We are now going to do a run to five g, with ten-second rise, holding on top for eight seconds.' Slowly the great arm began to revolve, then faster and faster.

On the arm itself, our tape was recording these words from the subject:

'I can feel the g coming on now. As if I were climbing away in an aircraft. I'm being pushed into my seat.' His voice began to come with more difficulty, as the gravity dragged at the muscles of his cheek and throat.

'Sinking down.' A second or two passed. 'I'm losing vision.'

'Vision completely gone now.'

So at this point the power was cut off.

'Coming back . . . Can see fairly clearly . . . Very difficult to move my hands.' Then in a more normal voice: 'Ah, the g's coming off now. Diving down . . . and coming to rest.'

As I have said, man will have to stand the effects not only of abnormally high gravity, but of zero gravity or weightlessness. He will be subjected to this condition not only in orbiting, but in the course of free fall, whether towards the moon or back to earth.

Weightlessness cannot be simulated on a machine like the one just described, but it has been studied, in America and in Russia, by sending small animals, such as rats, monkeys and dogs up in rockets. They have been recovered, apparently none the worse for this experience. Russian dogs, such as the celebrated Laika, have been sent up 300 miles in this way. But some experts claim that such animals have shown genetic changes as a result of exposure to radiation, indicating that the radiation belts may prove a more formidable barrier. It may be that a man will have to ration himself to a single space-flight in the course of his life.

Weightlessness can also be briefly induced by flying a plane in a curved path, in such a way that the centrifugal force produced balances out the force of gravity. The plane climbs and gradually turns over into a dive, following a parabolic curve. The US Airforce provided us with film taken inside an aircraft doing this. Floating in mid-air, and making frantic swimming motions, we saw Lt Gardner and Miss Jackson, a research worker at the Aero-Medical Laboratory, who is the first woman in history voluntarily to have experienced the effects of zero gravity. (See Plate 19.)

Another feature of high-speed flight studied by the RAF is the loss of orientation experienced by pilots after making violent twists and rolls. Our sense of balance is partly a product of what we feel in the semi-circular canals in our ears—a sort of system of carpenter's

levels which enables us to detect turning movements of our body even in the dark. But it is also governed by our ability to see the horizon. As flying experience has shown, people are much more inclined to rely on what their eyes tell them than what their balance-organs tell them, and the tendency to do this is more marked in some people than others. A pilot has to learn to trust to his instruments and to disregard his sense of balance and visual impressions. The crew of a rocket will have no horizon, while acceleration will bamboozle their balance-organs. We therefore need to know how far people can learn to ignore what their senses seem to tell them.

It is also useful to know precisely what movements produce what false impressions. One such false impression is that the pilot continues to feel that the plane is turning, after he has actually straightened out. He must therefore rely implicitly on his instruments at this point.

This tendency has been studied by sending a man up in a fast aircraft, with a film camera fixed on his headgear. The camera carries a periscope which enables it to photograph the movements of the wearer's eye in close-up. As the image is turned through two right-angles by means of prisms, it is, in point of fact, upside down.

To show this on *Breakthrough* we went down to Dunsfold Aerodrome, near Godalming. The Air Ministry had promised to provide us with a Hawker Hunter, a fast two-seater jet, for the day. Duncan Simpson was the test pilot. After shooting some close-ups of the head camera, we asked him to take-off at a given spot and go spiralling up into a blue patch in the sky, as a rocket goes screaming up into space. This he did with classic precision. Then he performed the key-evolution, known as a four-turn rapid roll. In this manœuvre, the aircraft turns at the incredible rate of 180 degrees a second, completing the four rolls in eight seconds.

When the special film taken by the eye camera was developed, we could distinctly see the pupil of the passenger's eye, flicking from side to side, and continuing after the manœuvre was completed. The eye twists round and round in its socket trying to keep a stationary picture of the horizon on the retina.

The passenger, an RAF doctor,* told me afterwards: 'The sensation

* To be quite exact, he was a former RAF medical pilot who was, at the time of the programme, a research fellow working at the Institute of Aviation Medicine under the auspices of the Medical Research Council.

is best described as the feeling you get when you turn round and round until you feel dizzy. As you know, after you've stopped, the whole room seems to be turning round you still.' This may be one of the problems facing man as he goes spinning out into space.

Another problem of space medicine is the heat-barrier which the vehicle has to penetrate on re-entry. This is not only a problem for the engineers but for the doctors. At Farnborough they are studying a similar situation in what is called the 'heat bath'. We made a film record of this, although in the end it had to be left out of the programme for lack of space.

One of the doctors took me into a small room, full of pipes. This was the 'heat bath'. More than half the space was taken up by a large aluminium box, with a curved lid, like a vast old-fashioned trunk, which occupied the whole length of one wall and over half the available floor-space. The bottom of this tank consists of a grille, so that the immense amount of perspiration produced by the subject can fall away. Experiment has already shown that a man can stand very high temperatures provided the air is dry—even temperatures so high that his hair is baked. But in damp air he is prostrated by much lower temperatures. The sweat must therefore be removed to prevent the air becoming humid.

The 'victim' climbs into this tank—normally he is naked for the experiment—and the lid is shut. Hot, dry air is then pumped in. Attached to him are devices which record the conductivity of his skin (which indicates his sweat-rate) his mouth temperature and other signs of his condition. These devices produce their readings on dials outside the tank, where an assistant stands, and the two men are in constant communication by means of microphone and head-set.

But it is the man in the tank who conducts the experiment. He asks the assistant to tell him, at intervals, his temperature and sweat-rate, and himself orders the shut-off.

As he leaves the tank, his face is literally dripping with perspiration. I wanted to include a shot of this, but by the time the camera had been moved into a suitable position, the perspiration had vanished. However, the doctor, with great good humour, said: 'All right, put me back and cook me up again.'

Five minutes later he emerged, perspiring heroically and observing: 'In that experiment, I suppose I lost at least two pounds. However, a couple of cups of tea will soon put that back.'

As all these stories show, the doctors who devise these experiments are their own guinea-pigs. I should like to stress this fact, for it is one which they modestly declined to say themselves in the course of the programme.

Nowhere is this truer than in the last experiment we showed: the attempt to simulate the psychological conditions of extreme isolation. Pilots flying at great altitudes have often reported the onset of an abnormal state of mind, apparently produced by the isolation. Some speak of it as a sense of elation, of power, of being in touch with God. Others have spoken of it as frightening. It vanishes as soon as they see another plane, or identifiable features of the earth's surface. One can imagine that in the depths of space such a feeling might be intensified.

This idea has sparked off research based on the idea of depriving people of *all* normal stimuli, whether of touch, sight or hearing. This is known as sensory deprivation. I knew that the RAF had been doing something on these lines. With some hesitation they agreed to let us show a piece of film which they had made, showing one of these experiments, and it made one of the most arresting sequences in the whole programme.

The scene is a great tank, resembling a small swimming-bath. Enter the subject, dressed in a woollen bathing-suit, with frog-flippers and breathing mask. (The mask is so designed that no effort is involved in breathing.) A shutter covers his eyes, so that he can see nothing but utter blackness.

He enters the water a little reluctantly, it seems, and is helped into position by the safety diver, who checks the apparatus and is present the whole time to give assistance if required. On his suit are hung floats and weights which prevent him moving up and down in the water as he breathes. The temperature of the water is regulated to blood heat, so that he feels neither hot nor cold, and neither loses nor gains heat.

As he floats there below the surface he inhabits a silent world, where he sees nothing, hears nothing, feels nothing. This is sensory deprivation at its most extreme level. His mind becomes isolated from his surroundings. He drifts into a dream state in which he may no longer be able to distinguish between sleeping and waking, between reality and hallucination.

Some people who have undergone this experience find it quite

soothing. One of them told me that he simply went off into a sleep. Others, according to American reports, have found themselves assailed by fantasies from the unconscious and finally by states of mind which they could not even describe. Yet others (probably given to claustrophobia, or fear of enclosed spaces) may find it disturbing and intolerable.

Certainly, such conditions seem liable to produce confusion of mind. The man seen in *Breakthrough* forgot he was under three feet of water, and actually tried to take his mask off when the experiment ended: he had to be rescued by the diver!

There can be little doubt that rockets will be fired to pass round the moon, and finally to land on it, within a very few years. What will be the next steps? The first, no doubt, will be to fire rockets in the directions of Mars and Venus, when their paths bring them in conjunction with the earth. Mars is, of course, the planet which revolves slightly farther from the sun than the earth: at its nearest conjunction it is about thirty-five million miles distant from us. Venus is the planet revolving somewhat closer to the sun than the earth: at its nearest conjunction it is twenty-six million miles distant.

Venus is thus about a hundred times as far away as the moon, while Mars is some one hundred and fifty times as far. You might think, therefore, that it would be a long time before this additional distance is bridged, but this is not so. As one moves away from the surface of the earth, the force of gravity rapidly falls off, according to the inverse square law. That is, when the distance doubles, gravitational force decreases by four times. When it trebles, gravity decreases by a factor of nine, and so on. A vehicle departing at 18,000 m.p.h. or more can escape entirely from the earth's gravity, and will then begin to fall towards the object producing the strongest gravitational field. Hence, to reach Mars, one need do little more than fire a moon-rocket in a direction which will carry it towards Mars, at a time when the moon is sufficiently remote from its path not to capture it. If an error in aim occurs, the rocket will not fall back to earth, but will continue on into space, and take up an orbit round the sun. It might, however, be captured as a satellite by some other planet, such as Venus, if it should pass near it. The probability, however, is that it will become a satellite of the sun.

It is not always clear to people why a satellite remains in orbit, and why a rocket fired at some heavenly body, such as the moon, is

liable to go into orbit round it, if it does not actually hit it. The satellite travelling round the earth has an angular velocity, and so develops a centrifugal force, and this exactly balances the pull of gravity. Why does not a slight disturbance upset this balance? What happens if the two forces are not exactly in balance?

Let us imagine a satellite travelling in a circular orbit, and suppose that the gravitational pull is stronger than the centrifugal force. As a result, the satellite falls towards the earth and thus its orbit gets smaller. As its linear velocity remains the same, in this smaller orbit, its angular velocity is increased. In simpler words, it now travels once round the world in a shorter time. But this increases the centrifugal force, which depends on angular velocity not on linear velocity. As it continues to fall finally the point is reached at which the centrifugal force is strong enough to counterbalaoce the pull of gravity.

In short, the balance between the two forces is not an unstable one. On the contrary, the satellite seeks just the precise path which will bring tbe forces Into balance. Of course, where the satellite's path is in air, not in a vacuum, it will tend to be steadily slowed down, and the centrifugal force will become weaker until it finally falls to earth. (We assumed, for the sake of simplicity, a circular orbit. The prioeiple holds good for elliptical orbits, though the analysis is more complicated, as the forces are continually changing.)

This is why it is necessary to aim very accurately to hit the moon, or any other heavenly body: a 'near miss' is not good eoough, as the satellite or rocket will go into orbit. However, if the speed of rocket is very high as it passes near the moon, though it will begin to fall towards it, it will reach the point at which it begins to move away from the moon before the gravitational attraction becomes strong enough to balance the centrifugal force, and from then on the gravitational pull will grow weaker. Therefore it will escape capture. All this also explains why a rocket which misses the planet at which it is aimed, is more likely to go into orbit round the sun than to fall into it.

Merely to hit the moon or Mars would be of limited scientific interest: it would be little more than a test of aiming and control. Indeed, as scientists have poiated out, a hit might eontaminate the moon with bacteria or viruses from earth; since there is much more likely to be some form of life on Mars than on the moon, the risk of destroying it and losing priceless scientific information, would be much greater. What would be most valuable would be photographs

or television pictures taken from a point fairly near the surface: better still would be the return of the vehicle to earth after circling Mars, with samples of its atmosphere, and of its soil and water, if any.

Though the efficiency of rocket motors improves steadily, we are not within sight of being able to build a rocket-propelled vehicle capable of carrying men to Mars, let alone of bringing them back. The most we can envisage is carrying men to the moon, though here the problem is how to land on that airless satellite, without wrecking the vehicle. Columbus is always remembered as the man who first sighted the New World; obviously the fame which will attach to the first men in the moon will be even greater. I have little doubt that the Russians are determined to beat the Americans in this race, and that therefore we shall see men in the moon before long.

If once the moon becomes accessible, the chances of conveying men to Mars or Venus are much improved. For rockets which depart from earth spend an enormous amount of energy escaping from its strong gravitational field, and still more on pushing through its comparatively dense atmosphere. To escape from the moon, which has no atmosphere and a gravitational field one-seventh that of the earth's, would be far easier. Hence to build a rocket capable of carrying several men from the moon to Mars and back would be a quite manageable technical problem. I should therefore expect an attempt to ferry up to the moon the parts of a suitable space-vehicle, as soon as it can be reached with reasonable reliability. These parts would then be assembled on the moon, and the vehicle launched from there.

What lies beyond rocket-fuels? Scientists are discussing the idea of adapting the accelerators used to speed up fragments of atoms—ions—to high speeds as a source of energy. The mass of material which such an accelerator ejects is very small; on the other hand, the speed of ejection is phenomenally high; a linear accelerator can easily accellerate ions to a velocity of about one-third the speed of light, or 62,000 miles per *second*. As already mentioned, the thrust on the rocket is a product of the speed of the ejected material multiplied by its mass—here the smallness of the mass is compensated by the tremendously high speed. Such a device would therefore be able to carry fuel sufficient for very long voyages. What it would need, in compensation, would be large amounts of energy to power the

accelerator. This would have to be provided, presumably, either from nuclear sources, or, better, from the energy of the sun, by photoelectric devices. At present, of course, we are not within sight of being able to build photo-electric devices which would provide the kind of voltages necessary, within the kind of space which would be available.

Another possibility is the building of a large satellite, or space station. Mr Krafft Ehriche, head of Convair Astronautics Inc. of California, expressed the opinion to us that a space station carrying four men, and based on the Vanguard missile, could be put into orbit at about 300 miles altitude approximately five years from receiving permission to go ahead with the project.

Fred Hoyle, the cosmologist, who appeared in the programme, took the view that no man should be allowed to clutter up any satellite. 'Instruments, instruments and more instruments, that's the scientists' watchword,' he said. 'Men just don't have the right sort of eyes to look out on the new world that's now opening up before us.' Nine-tenths of the information which comes to earth from outer space, carried by ultra-violet light, X-rays and so forth, never reaches us down on the surface of the earth. It gets absorbed in the gases of the atmosphere. We're forced to live blind, like moles, never knowing what's going on in the big world outside. To overcome this, the astronomers would like to get a telescope up above the atmosphere by mounting it on a satellite. One day that will be done.'

All this takes a great deal of money. A Vanguard rocket costs about a million pounds, the lunar probes cost about five millions a time. But man's questing spirit is not likely to be restrained by such considerations. As Professor Massey said, in introducing the second edition of *Breakthrough*, early in 1959: 'The first man to land on the moon has already been born.'

13

A Look at the Scientists

TELEVISION can convey something of the work of scientists. It can show its painstaking nature, and how it is possible to draw conclusions about things which can never be seen or experienced at first hand. But it has not yet found a way to tell us much about the scientists themselves.

True, it can dispel some of the popular illusions fostered by horror film and comic strip. Anyone who looked at *Eye on Research* could see that the scientists were not remote, inhuman figures, locking themselves away in laboratories for years to emerge finally with some devastating discovery. Most of them were youngish men, in their thirties or early forties; most of them talked freely about their work. Nor did they resemble the popular notion of the eccentric egg-head, with beard and egg-stained waistcoat, talking nineteen to the dozen and throwing off brilliant ideas. I do know one or two scientists who correspond roughly to this description; but they are exceptional.

It was also obvious that none of them worked in isolation. Most were members of a team, or depended on the work being done in other labs in many parts of the world for their own progress. Science has become too complex for the brilliant individual to work completely on his own, in most spheres. Many of them employ equipment too costly and elaborate for anyone but a large industrial concern or a government department to buy and maintain. In contrast, some of them—chiefly in the biological sciences—work with little apparatus besides a microscope and a few old tobacco-tins to hold their material. I saw little more than this, for instance, in the lab in Glasgow University, in which Dr J. A. Roper is making important studies in genetics by observing an obscure mould called *Aspergillus*.

But this does not tell us what sort of a man the scientist is. What are the motives which impel him? Does he worry about the social

consequences of his work? How is that work chosen—how far is it the following of a personal hunch, how far is it selected for him by others? Who, in fact, controls the direction of scientific research?

And does the scientist, it is also interesting to ask, still see the universe as a vast machine? Has the unpredictable element, which now is recognized in the physical as well as the biological sciences, given him a less deterministic, or even a more religious view?

The many conversations I had with scientists during the production of these programmes gave me some tentative answers to such questions, hard as it is to generalize about a body of men which, naturally, contains many diverse elements. It is important to distinguish, also, between the 'pure' scientist, and the one doing applied work.

The pure scientist is often, I think, a man who finds handling other people, and working under pressure from other people, exhausting and disagreeable. He prefers a job in which he can go his own pace, without too much supervision. At the same time, solving an intellectual problem has, for him, the same sort of absorbing interest that solving a crossword puzzle or winning a chess game may have for other people, though at a far higher level of intensity and sustained over a far longer period. To say, as scientists sometimes do, if pushed, that their motive is pure curiosity, is misleading: it is more than that.

What such statements mean, I think, is that the scientist does not wish to suggest that he does his work from disinterested love of the human race. There are cases, especially perhaps in the medical field, where a desire to relieve human ills figures largely, but this is clearly not so when investigating, let us say, problems of rocket flight.

In saying that the scientist likes to go his own pace, I do not wish to convey that the pace is an easy one. Most of the 'pure' scientists I have met work themselves hard, often staying late or working at week-ends. Often they have been much concerned by the interruption of their work by even one day in the cause of making a television programme.

I do not think it is unfair to say that the 'pure' scientist is extremely anxious for recognition among his colleagues. This is a universal human motive. Science is, intellectually speaking, highly competitive. Many a scientist is worried by the idea that, after he has worked for possibly five years or more on a problem, a friendly rival, working

on the same problem in another lab may find the answer first, and so attain renown. A man's career in science depends a great deal on whether he can produce original work. The committees which give grants for research watch for talent, and if a man has failed two or three times to make a contribution he may find it increasingly hard to get support. Ahead of all scientists loom two targets, the professorship and the FRS, or Fellowship of the Royal Society. Around the age of forty, he begins to worry about his FRS, and more than one scientist has been soured, and his work has deteriorated, from his failure to win the coveted distinction. Though the FRS carries no monetary reward, it makes the scientist's chance of reaching professional rank far better, and this rank, of course, carries the highest rate of pay to which he can normally expect to attain.

Having said all this, I must add that for many scientists there is a genuinely aesthetic element in scientific work. When a man devised a simple yet accurate way of obtaining a set of facts which previously no one knew how to determine, it is called 'an elegant technique' and the adjective is used in its precise dictionary sense of neat and graceful. The harmony of function of each aspect of the universe which the scientist studies appeals to him, very often, as aesthetically satisfying.

The scientist working on applied problems is much less likely to achieve intellectual renown—though this sometimes happens—but he has the satisfaction of contributing to a visible practical achievement. The rocket finally soars into the sky for all to see; the silted river runs free. And if he is in industry, he is usually rather better paid.

It is my impression that most of the scientists I have met feel that all the phenomena of the universe can be analysed, in the sense that a coherent account of how, and in what circumstances, they occur can one day be given. This doesn't necessarily make them materialists—people who believe that the universe is nothing but a 'fortuitous concourse of atoms'—though many of them are. But it does mean that almost all of them would be prepared to bet that life, for example, can be accounted for entirely in terms of physics and chemistry. They do not see it, as theologians do, as a miracle divinely bestowed. They have seen too many phenomena, which were once thought miraculous, turn out to be natural, to believe that what is still unexplained will not succumb to reason likewise.

One of the discoveries made in this century—and it is a major

discovery indeed—is that an element of chance or uncertainty figures in physical processes, as it also does in biological ones. No one can say when a particular radioactive atom will blow up, and there are limits to the accuracy with which (for instance) it is possible to describe the path and position of an electron as it orbits round an atomic nucleus. Some philosophers have tried to argue from this that, since science cannot ever hope to predict precisely what will happen, the universe cannot be regarded as a machine: and from this they conclude that there is still room in the universe for a religious element.

In actual fact, it is easy enough to construct a machine which contains elements of chance: ERNIE, which selects the winning premium-bond numbers, is a well-known example. So the discovery of this element of randomness does not prove that the universe cannot be regarded as a vast and complex machine.

However this may be, the average scientist has not, I think, altered his views much as a result of these discoveries. I doubt if he thinks about them any more than the average man: that is, he does if he has a philosophical bent, but not in his role of scientist. It must be remembered that the individual scientist is necessarily a man who has chosen to know a great deal about a very small area of knowledge. Science is very much a matter of specialization, these days. The eighteenth-century idea of the polymath, the man with a knowledge of all sciences, has become harder and harder to realize. A few scientists still attempt it, but only a few.

What is it, then, which determines the area in which a scientist will work? This question implies another: how is the general direction of scientific research controlled and decided?

It is decided by an ingenious, and in many ways highly effective compromise. On the one hand, there is pressure to solve certain problems which it is in the public interest to solve: for instance, to find a really effective method of treating cancer, to produce fusion-power from the atom, to discover what goes on in the upper atmosphere. On the other hand, there is the fact that one cannot start researching on a problem unless some way of studying it exists or can be devised.

The public does not fully realize how very difficult it is to find any method of studying certain problems. For instance, it would be very useful to know just what the chemical messengers known as

hormones do when they reach the cells which they regulate. This has been a crying need for half a century, but our ignorance is still nearly total, simply because there is virtually no effective method of studying this. Similarly it is impossible to study *directly* what cancer-causing substances do to the body-cells. The scientist therefore has to work by inference, and to approach the subject by such oblique routes as he can find.

Consequently, the pattern of pure research is settled, to a very large extent by the interplay of two processes. First, those in charge of research funds look favourably on proposals which look like solving some practical problem, or providing basic knowledge which someone will eventually need in order to solve it. The scientist, knowing what kind of project is most likely to be accepted and receive financial support, thinks how in fact he could do research on it, and chooses a line of experiment which looks both practicable and promising. What he personally finds interesting naturally influences the proposal he makes. But a survey made soon after the war revealed that only about one-third of the scientists polled would have been working on their subject if they had had completely free choice. The possession of private means is still an important factor in scientific research.

In making his choice, he is very much influenced by the research methods which happen to be currently available. Thus, for instance, when Professor Porter showed how the electron microscope, previously only used for the study of metals and other inorganic materials, could be adapted to the study of organic materials, there was a general rush to apply it to such material and a flood of discoveries resulted. Other recently-invented techniques, such as the newer kinds of chromatography, have been exploited in the same way. Broadly, therefore, it is true to say, that the course of research is governed, more than anything else, by the tools and techniques available. The man who invents a radically new technique does more for science, it may be thought, than any given scientist who makes a discovery with that technique.

In a rather similar way, progress may be held up for lack of a piece of basic knowledge: when this knowledge is provided, scientists rush to apply it. The discovery of the significance of DNA, for instance, set off an enormous number of experiments in different labs all over the world, an attack which is still going on. Scientific progress is also

influenced by the discovery of new ways of looking at problems. The notion of 'feed-back' (see Glossary) originally introduced in electronics, was soon applied to medical, social and biological problems. Looking at such problems in this new light soon suggested new ways of studying them.

In short, the progress of science is fundamentally pragmatic, even haphazard. And to a certain degree it must always be so.

Yet I doubt if it need be quite so haphazard as it is. For instance, very little general thought is given to the question of 'researchability'. Students receive no training in how to put problems into a researchable form, except the sort of practical training which Mr Squeers used at Dotheboys Hall. The average young scientist receives his initiation when his professor directs him to explore some limited problem which is usually a sub-section of what the professor himself is trying to do. The young scientist, in the course of this work, comes across or thinks up some further problem, usually arising out of or akin to the first. Thus his life-course is settled by what his professor happened to be working on, even if the subject itself is not the same.

Such practical experience is indispensable, of course. But the net effect is apt to be that certain problems get neglected. In selecting his own problem, the young scientist relies upon his own very imperfect knowledge of what is researchable; he will consult his professor, but he in turn may not be much better placed to decide. There is, in short, no one whose job it is to think about the problems of science as a whole, and how they may be tackled; or even about the problems of any given science. The directors of research institutes are busy men, with much administration on their shoulders. Research funds are controlled almost entirely by men who give a little of their time, in the midst of many other activities, to considering the question, aided by administrators who are often not even scientifically qualified. Their practical experience is vitally important: they are often able to eliminate impractical suggestions or to avoid duplication. But they are rarely men who have had the opportunity to brood on the research field as a whole.

In the U.S. the Institute of Advanced Studies at Princeton (another is being founded in California) provides certain opportunities for general thought of this kind. In Britain there is, unfortunately nothing similar.

The trouble with this pragmatic method is that it brings about research on what is fairly obvious, but leaves unexplored various parts of the map of knowledge which are not conveniently accessible. Unfortunately, it is often just these 'blind spots' which conceal what is truly novel and enlightening. Perhaps a recent example of this is the discovery, made by Professor J. D. Bernal (who bas always been noted for originality of approach) that not only solids, but also liquids, can have a crystalline structure.

Until last year, orthodox science taught that only solids could be crystalline, and it occured to no one to look for structure in liquids. Had some new-fledged scientist proposed to study such a subject, the grants committee would, without the slightest doubt, have turned it down as a thoroughly unsound idea, and would probably have regarded him as slightly mad.

The steady-going senior scientist may well lack the imagination to see the possibilities which a younger man may see in a particular project. It is interesting that F. J. Sanger, who recently won the Nobel prize for his success in establishing the chemical formula of insulin after ten years work, was discouraged strongly from attempting anything so difficult, and for a long time bad to do the work in the evening as a supplement to supposedly more practical activities.

Since no one had ever succeeded in establishing the structure of any member of the highly complex class of compounds known as proteins (of which insulin is one) before, it was thought to be virtually impossible.

The fact is, truly original and creative brains are as rare in the field of science as elsewhere. Most scientists depend on extreme care and accuracy, steady persistence in accumulating facts. Very few have the flair to put such facts together and reveal the pattern in them. And it must be confessed that those who are endowed with this creative gift are often viewed askance by their colleagues who are inclined to feel that they reap the fruit of others' toil.

Since I noted, earlier in this chapter, my impression that few scientists worry about the philosophical implications of their activities, I must, before concluding, record that many of them do worry today about the social implications, and about the whole question of the relationship between scientists and the public. I have never met a scientist who did not feel he had a duty to make his work intelligible to the public; it was because of this attitude of mind that

Eye on Research was possible. In almost every case scientists made themselves free at short notice to discuss their work with us, and, when it came to transmission, bore the disturbance to their work and their laboratories with good humour and patience.

Many scientist do not know how, without aid of this kind, they can meet this responsibility. They seldom have great facility in simplifying their own work: some can do it when using the spoken word, but few can write about it. They feel that the public's lack of understanding of basic scientific terms constitutes a barrier which is extremely difficult to overcome.

But this is a situation which may be improving, for the audience research reports on *Eye on Research* suggest that viewers under thirty, or thereabouts, have much less difficulty in understanding the programmes than those over this age. Too often, the older viewer tends to reject science as beyond his grasp, and even as rather frightening. This is a policy of despair, for science has certainly come to stay, and we must find out how to come to terms with it.

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Endpiece

MANY people find the world of science confusing: so many different kinds of researcb seem to be going on, that it is very difficult to see *any pattern in what is being done. It is true, of course, that scientists* attack the unknown at many points and any individual is free to pick for study aoy problem which interests him. Nevertheless, certain general trends can be observed, provided we use science in the strict sense of 'exact knowledge'—i.e. physics, ebemistry and biology.

Io the fields of pure knowledge, science has become increasingly successful at exploring the very large and the very small—particularly the latter. In fact, the structure of the very small—the fine-grain of the universe, so to speak—has become so well uoderstood that science is turning to slightly larger structures. Thus, in the field of chemistry, the simple molecules have been thoroughly explored, and chemists are oow studyiog much more complex molecules, such as the silicooes, the chemistry of which involves such unpronounceable terms as dimethylpolymethyleoedioxysilaoe, and molecules with particularly interesting structures—which give them particularly interesting properties—such as the porphyrins. Those molecules have a ring-structure which enables them to grab bold of certain other atoms. These are useful in industry, e.g. for water-softening; in medicine, e.g. for dissolving kidney stones; in the living being (they form part of blood haemoglobin and enable it to take up oxygen) and in the laboratory, where they are revolutionizing chemical analysis.

Meanwhile the biochemists are going on to explore complex molecules in the living organism, such as the vitamins, insulin, and the nucleic acids, whicb we have already discussed. The physiologists are turning up scores of complex substances which exert controlling effects within the body, such as angiotensin and vasopressin, which are concerned with regulating blood-pressure, or serotonin, which

has so many tasks that scientists are still busy working them out. All these then provide problems for the biochemist, who seeks to establish their structure, and to create them artificially in the laboratory.

Much the same thing is happening in the field of biological structure. Here many biochemists are busy with the very large molecules known as proteins. Protein molecules consist of long chains, but these chains are folded and coiled in complex ways, as yet almost unexplored, and the study of these foldings will keep biophysicists busy for many years. A start has been made by Dr Kendrew at Cambridge, who has established the system of folds in myoglobin, a kind of haemoglobin found in muscle, and this year the structure of haemoglobin itself has been established by Dr Perutz.

The physicists, likewise, know a great deal about the atom; some of them are concentrating on things a bit larger, such as crystals, which are serried ranks of atoms, and are finding unsuspected facts about how they behave, how energy passes through them. Such work has already given us the transistor, now used in miniature radios and deaf-aids, and other devices of the same sort.

It is a basic principle of science that the way a thing behaves depends on how it is constructed; or, in more precise terms, structure and function are interrelated. Science generally starts by exploring structure, then goes on to establish function. For example, the microscope shows that the body consists of cells: the next question is, what purpose do they serve in the life of the body, what function do they perform. When the electron miscroscope reveals unsuspected structures within the cell, again the question arises: what are they for?

In other cases, people notice some strange phenomenon: something which behaves in a way which surprises them. It may be simply that when two clear liquids are shaken together, a solid substance appears and falls to the bottom of the test-tube. Or it may be a complex piece of human behaviour, like the pilot's loss of his sense of balance after a roll. In their attempts to explain such phenomena, scientists study the structures which produce it.

This to-and-fro movement can often be seen in science. When a technical advance reveals new structures, there is an immediate spurt of development in the job of explaining their function.

The progress of science depends to an enormous extent on the development of new tools. The pure insight of a Newton or an

Einstein is rare; when a scientist has a moment of insight, it is usually after other people have turned up a lot of puzzling facts, which he discovers how to put together. Consequently, the trend of science can most easily be discerned by considering what new tools have recently been evolved. At the present moment there are three of particular importance—we have come across all three of them in this book, more than once.

The first is the electron-microscope, which has opened up the structure of materials and of objects a few millionths of a millimetre across. I have told of its use in the study of viruses. It is equally useful in exploring the fine structure of metals, and is showing metallurgists why metals are not as strong as, on the face of it, they should be.

The second is the oscilloscope: fundamentally, this is a device which enables us to chop time up into very small fractions. I told how phoneticians use it to analyse speech, but it can chop much finer than this. Atomic physicists use it to distinguish events—such as the disintegrations of a subatomic particle—which are a few billionths of a second apart.

The third is chromatography, which enables the scientists to make almost incredibly fine analyses, separating very small quantities of very similar substances from one another. It has countless applications, but perhaps its most striking are those in the biological field, where it is difficult to get more than trifling amounts of the substance to be examined, and where ordinary analytical methods would break the substance up completely.

Just exploiting the fields opened up by these three tools—and there are others—will keep scientists busy for years. If we add to this the fact that radioactive materials are available far more freely than before, the point is even more strongly made. Particularly interesting here is the technique of 'labelling' a molecule by including a radioactive atom in its make-up. The molecule can then be traced on its course through the body; while, in *Trial by Water*, I mentioned a quite different use, the tracing of water-currents. Similarly it can be used to study tyre-wear or what happens to lubricating oil. This is an advance in method of major importance in the growth of science.

The existence of radioactive materials has also created a whole group of research fields, such as 'hot' chemistry or the chemical behaviour of radioactive compounds, and health physics, or the effect

of radiation on living things. Radiation also affects the physical properties of substances, turning a rigid plastic rod into a flexible or waxy one. The creation of new tools always opens up new problems to solve, and scientists show no signs of running out of material.

That scientific research covers a wide range is obvious. After my experiences in preparing the programmes described in this book, and others which have appeared in the *Eye on Research* series, I am left with an impression which is perhaps less obvious. I am powerfully struck by the amazing speed with which scientists are clawing down the curtains of the unknown in many fields. We have become so used to reading reports of scientific progress—and so much is left unreported—that few of us realize that we live in an age of discovery which will, in after ages seem a golden age of science. It is an age not merely of discovery, but of consolidation: of broader and broader understanding of the mechanisms of man and of the universe.

History suggests, in my opinion, that such rapid progress cannot continue indefinitely. If the scientists themselves do not run into a scientific 'sound-barrier' (that is, a point at which many problems are disclosed which appear to be totally insoluble) then history may take a hand. Science itself may create such strains on society that it will collapse into a new Dark Ages, in which much of what has been learned will be forgotten.

To live in such an age is a remarkable privilege, if an alarming one. But it is a difficult privilege to profit by, since the range and complexity of science make it difficult to understand many of its most significant discoveries, and harder still to gain any general perspective.

This should not make the privilege any less stimulating. The sense of ever-profounder discoveries around the corner should bring a sense of excitement to everyone possessed of a spark of intellectual curiosity.

Bibliographical Note

Most of the work I have described is so recent that it has not been described except, in some cases, in technical papers. But Dr Mason has described his subject in *The Physics of Clouds* (1958). Problems of rocket propulsion and space flight were described in *Penguin Science News*, No. 48 (1958). *Satellite!* by E. Bergaust and W. Beller appeared at the end of 1957.

Prof J. A. V. Butler's *Inside the Living Cell* (1959) is an excellent introduction to the newer aspects of biology, and contains good chapters on the nucleic acids, viruses, etc. So does *The Physics and Chemistry of Life*, a reprint of various articles from the *Scientific American*, published in Britain in 1957. K. M. Smith and R. Markham, *Mumps, Measles and Mosaics* (1954) can be recommended as a popular study of viruses, as far as the subject had been explored at that date. *Bacteria*, by K. A. Bisset and F. W. Moore is a short introduction to the subject of bacteriology.

Those who saw the programme on computers, *The Brain in the Box*, may like to read *Faster, Faster* by W. J. Eckert and R. Jones, and those who saw *A Mind of Your Own*, can read Grey Walter's own account of his work in *The Living Brain* (1953).